(NASA-SP-468) QUEST FOR PERFORMANCE: THE EVOLUTION OF MODERN AIRCRAFT (Loftin (Laurence K., Jr.)) 548 p HC A23/MF A01; SOD HC $26.00 as 033-000-009 CSCL 01B

N85-32089

Unclas

H1/01 20918

ORIGINAL CONTAINS COLOR ILLUSTRATIONS

Quest for Performance

The Evolution of Modern Aircraft

NASA SP-468

Quest for Performance

The Evolution of Modern Aircraft

Laurence K. Loftin, Jr.

NASA Scientific and Technical Information Branch 1985
National Aeronautics and Space Administration
Washington, DC

On the cover (left to right): British Sopwith F.1 Camel fighter (photo by William T. Larkins, courtesy of American Aviation Historical Society); North American P-51D fighter (photo by Peter C. Boisseau); North American XB-70A supersonic bomber (photo courtesy of North American Aviation)

Loftin, Laurence K.
Quest for performance.
(NASA SP ; 468)
Includes bibliographies and index.
1. Airplanes—History. I. United States. National Aeronautics and Space Administration. II. Title. III. Series.
TL670.3 L63 1985 629.133'34'09 83-17262

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

Contents

Preface

More than 75 years have passed since the Wright brothers' historic first flight of a powered, heavier-than-air aircraft at Kitty Hawk, North Carolina, on December 17, 1903. During this relatively brief period, the airplane has developed from a useless freak to a highly significant force in modern society. The transformation of the airplane during this period must be ranked as one of the great engineering accomplishments of all time. The magnitude of the achievement is emphasized by the nature of the vehicle and the rigorous requirements for precise design of every element. In no other type of machine, with the possible exception of space vehicles, do the often conflicting requirements of performance, safety, reliability, and economic viability place such a high premium on detailed design optimization, based on quantitative data and analysis.

The evolution of the airplane since 1903 rests on technological advances in such fields as aerodynamics, stability and control, propulsion systems, structures, materials, internal systems, and manufacturing technology. Advancements in all these areas have been made possible by millions of man-hours spent by highly motivated people. Private individuals, research laboratories operated by civil and military elements of the government, and universities—as well as industrial design, research, engineering, and manufacturing teams—have all contributed to the development of the airplane. The evolution of the modern airplane has been characterized by a series of technological levels, or plateaus, that extend over a period of years. Each level has been exemplified by an aircraft configuration type that is gradually improved by a series of relatively small refinements, without any major conceptual change. Under the stimulus of some form of competition, new technology in a number of disciplines has occasionally been combined synergistically in a new design to produce an aircraft of a new and higher level of technology. The Douglas DC-3 transport is a good example of this type of advancement. In a few rare instances, a revolutionary breakthrough or

new concept has dramatically altered the course of aeronautical development and established a new and higher technical plateau. The advent of the jet engine and the concept of the swept wing for high-speed flight fall into this category.

Although some further refinement was possible, the technology of the propeller-driven airplane equipped with a reciprocating engine was, at the end of World War II, on a plateau with little expectation of major improvement. In the face of this depressing prospect, aircraft equipped with a new and revolutionary type of propulsion system, the jet engine, appeared on the scene in the closing months of the war. This innovative propulsion system introduced an entirely new level of technology in aircraft design. The subsequent advances in aircraft performance and capability made possible by the turbine engine have perhaps been even more spectacular than those characterized by the first 40 years of powered flight. The initial applications of jet propulsion were to military aircraft of various types. Indeed, the military airplane and the concepts of its various missions went through a complete metamorphosis as a result of this new type of propulsion system. The first jet-powered transport entered commercial operations in 1952. This event heralded the beginning of a revolution in domestic and international air transportation that has accompanied the development and refinement of this type of transport. The entire concept of common-carrier transportation has been radically altered by the jet transport.

This volume traces the technical development of the airplane from a curiosity at the beginning of World War I to the highly useful machine of today. Included are significant aircraft that incorporated important technical innovations and served to shape the future course of aeronautical development, as well as aircraft that represented the state of the art of aeronautical technology in a particular time frame or that were very popular and produced in great numbers. In order to reduce the scope of material under consideration, primary emphasis has been placed on aircraft originating in the United States (except in chapter 2). No adverse reflection on the quality of the many fine foreign designs developed over the years is intended by their exclusion. The aircraft described certainly do not include all the significant types designed in the time period 1914–80, but they do illustrate the primary features of the technical evolution of the airplane. If the reader's favorite aircraft is not included, the reference lists at the end of this volume include publications that catalog data and photographs for a wide variety of aircraft.

The discussion is related primarily to aircraft configuration evolution and associated aerodynamic characteristics and, to a lesser extent, to developments in aircraft construction and propulsion. The book is divided into two parts. Part I deals with the development of propeller-driven aircraft, and part II is devoted to subsonic jet-powered aircraft designed for civil and military use. Some of the jet aircraft described are capable of brief excursions into the realm of supersonic flight; however, long-range supersonic-cruising aircraft are an entirely different class of vehicle and are not discussed in the present volume.

The material is presented in a manner designed to appeal to the nontechnical reader who is interested in the evolution of the airplane, as well as to students of aeronautical engineering or others with an aeronautical background. The use of engineering terminology has been kept at a minimum, consistent with accuracy and the intent of the text; where unavoidable, suitable physical explanations have been included.

Acknowledgments

The author wishes to express his appreciation for the assistance provided by many present and former staff members of the NASA Langley Research Center in the preparation of this publication. In particular, the helpful comments and suggestions of Mr. Thomas A. Toll, who reviewed the entire manuscript, are gratefully acknowledged. Others who reviewed individual chapters and offered useful comments are Dr. John E. Duberg and Mr. Mark R. Nichols. Thanks are extended to the various sources for the photographs used in this book; credits are listed in the figure captions. Mr. Peter C. Boisseau and Mr. Martin Copp were particularly generous in providing photographs from their extensive collections. Finally, thanks are gratefully extended to Ms. Dorothy E. Coleman, who so expertly edited the manuscript.

Part I

THE AGE OF PROPELLERS

Chapter 1
Introduction

The first flight of a powered, heavier-than-air aircraft was, of course, made by Orville Wright on December 17, 1903. In the decade following this historic event, aircraft development was characterized by a proliferation of types, conceived primarily by inventors of varying degrees of competence. A few of these aircraft flew moderately well, some poorly, and some not at all. There was little scientific and engineering foundation for aircraft design, and many aircraft built during this period were constructed by nontechnical people as amateur, backyard-type projects. Most of these aircraft were designed for no other mission than to fly, and most were employed for exhibition purposes, races, or other spectacular types of events. No definitive aircraft configuration types had emerged by 1914, the beginning of World War I, and flying was regarded by most intelligent people—if at all—as a sort of curiosity not unlike tightrope walking at the circus. These viewpoints were utterly changed by the tactical and strategic uses of aircraft in the First World War. The demands of combat aviation, together with the opposing powers constantly vying for air superiority, resulted in the development of the airplane from a curiosity in 1914 to a highly useful and versatile vehicle, designed to fulfill specific roles, by the end of the war in November 1918.

The evolution of propeller-driven airplanes from 1914 to the present falls into five distinct, identifiable time periods that provide the framework for chapters 2 through 6. Significant design trends, as evidenced by changes in aircraft physical and performance characteristics, are discussed in chapter 7. Chapters 2 to 7 are restricted to a discussion of aircraft designed to operate from land-based fields and airports. Consequently, the flying boat, once an important class of aircraft but now almost extinct, is not included in these chapters; however, a brief description of the evolution of this unique and picturesque type of aircraft is contained in chapter 8.

As indicated in the preface, the discussion is restricted primarily to aircraft types developed in the United States. Chapter 2 on World War I aircraft is an exception; European aircraft form the basis for the material presented in this chapter since the United States developed no significant combat aircraft during the war years 1914–18.

The aircraft discussed in the following chapters, together with some of their physical and performance characteristics, are listed in tables I to IV in appendix A. The quantities tabulated are defined in the list of symbols contained in appendix B, and generally require no further elaboration. However, three of the aircraft aerodynamic characteristics presented deserve some further discussion. These are the zero-lift drag coefficient $C_{D,0}$, the drag area f, and the value of the maximum lift-drag ratio $(L/D)_{max}$.

The zero-lift drag coefficient $C_{D,0}$ is a nondimensional number that relates the zero-lift drag of the aircraft, in pounds, to its size and the speed and altitude at which it is flying. Generally speaking, the smaller the value of this number, the more aerodynamically clean the aircraft. For example, the value of $C_{D,0}$ for the North American P–51 "Mustang" fighter of World War II fame is about 0.0161 (table III) as compared with about 0.0771 for the Fokker E–III fighter of World War I (table I). Accordingly, the P–51 is a much cleaner aircraft than the Fokker E–III.

The drag area f is the product of the zero-lift drag coefficient and the wing area. The resulting number is of interest because it represents, approximately, the area of a square flat plate, or disc, held normal to the direction of flight, which has the same drag in pounds as the aircraft at a given speed and altitude. (The relationship is exact for a flat-plate drag coefficient of 1.0. According to reference 72, the actual drag coefficient of such a plate is 1.171.) For example, the drag area of the P–51 fighter is 3.57 square feet as compared with 12.61 square feet for the much smaller Fokker E–III of World War I. The improvement in aerodynamic efficiency over the 25-year period separating the two aircraft is obvious. Comparisons of the drag area of aircraft of different periods designed for the same missions can thus provide some indication of comparative aerodynamic cleanness or streamlining. Furthermore, the maximum speed is approximately proportional to the cube root of the ratio of the power to the drag area (ref. 90). The larger this ratio, the higher the top speed.

The value of the maximum lift-drag ratio $(L/D)_{max}$ is a measure of the aerodynamic cruising efficiency of the aircraft. In essence, it is inversely related to the amount of thrust required to sustain a given

weight in the air and is proportional to the miles of flight per pound of fuel for a given propulsion system efficiency and aircraft weight. The higher the value of $(L/D)_{max}$, the higher the cruising efficiency of the aircraft. The value of the maximum lift-drag ratio is a function of the zero-lift drag coefficient and the drag associated with the generation of lift. The drag-due-to-lift is, in turn, related to the wing aspect ratio (basically, the ratio of span to average chord) and becomes smaller as the aspect ratio is increased. The value of the aspect ratio A is given for each of the aircraft listed in the tables. Values of $(L/D)_{max}$ for propeller-driven aircraft vary from about 6.4 for early World War I fighters to about 16 for transports such as the Lockheed 1049G of the 1950's. The values of $C_{D,0}$ and $(L/D)_{max}$ given in the tables were estimated from published aircraft performance data according to the methods described in appendix C.

The references used in obtaining the characteristics of the aircraft are listed in tables I–IV or are specifically cited in the text. *Jane's All the World's Aircraft* (refs. 1–16) has been used extensively in compiling the characteristics of the aircraft presented in the tables. This definitive series of books has been published each year since 1909 and forms an invaluable source for anyone interested in aircraft development. A few references that provide useful background material, but which are not specifically cited in the the text, are offered for additional reading on the subject of aircraft development. For convenience, references 17 to 124 are listed alphabetically.

Chapter 2
Design Exploration, 1914–18

Background

A multitude of aircraft types were tested in combat in the war period 1914–18, and literally hundreds of prototypes were built and flown. These numbers become believable when one considers that the prototype of a fighter aircraft could be designed, constructed, and test flown within a period of a few weeks. In contrast to the essentially job-shop approach to aircraft construction that prevailed prior to 1914, an aircraft industry was developing, nurtured by large expenditures of money by the belligerent governments. The engineering principles of aircraft design were also beginning to take shape. Government laboratories, such as the Royal Aeronautical Establishment in England, contributed greatly to the foundations of aeronautical engineering. Scientific and engineering laboratories also existed in France, Italy, and Germany; and the National Advisory Committee for Aeronautics (NACA) was established in the United States by act of Congress in 1915. The results of NACA research, however, did not begin to have a significant impact on aircraft design until the mid- to late 1920's. In contrast to the European powers, the United States had essentially no air force and no real aircraft industry when war was declared on Germany in April 1917. Accordingly, the United States relied almost entirely on tried and proven European aircraft designs. Many of these aircraft were produced by European companies for use by the American Expeditionary Force, while others were manufactured under license in the United States.

Aircraft types of amazing variety were built in the continual quest for better fighting machines. Monoplanes, biplanes, and triplanes were employed in military operations at various stages of the war, and several quadruplanes were tested in prototype form. The wings of most of these aircraft were supported externally by a combination of wires and struts, although several designers developed aircraft with internally

braced cantilever wings. Perhaps the most notable was the Dutch designer Anthony H. G. Fokker, who supplied many cantilever-wing fighter aircraft to the German air force. Both pusher- and tractor-type engine installations were employed, and multiengine bombers frequently utilized a combination of pusher and tractor powerplant installations. The pusher-type configuration was used extensively as a fighter, particularly by the British, in the early stages of the war. The internal structure of most of the aircraft consisted of a wooden framework braced with wire and covered externally with cloth. Some aircraft employed a mixture of metal and wood in their construction, and experiments were conducted with all-metal aircraft whose wings were internally braced. Dornier and Junkers in Germany were among the pioneers in all-metal aircraft construction. The types of alloys available at the time, however, did not lend themselves to the light weight required in aircraft design, and the concepts of light, stressed-skin metal construction lay in the future. All-metal aircraft did not play an important role in World War I. The use of plywood as an external covering, together with a minimum of internal structure, particularly in fuselage design, was also employed by several manufacturers. This type of construction, called monocoque, is described in more detail later.

Two vastly different engine types were employed in World War I aircraft: the stationary engine, usually water cooled, and the rotary engine. Water-cooled engines of 4, 6, 8, and 12 cylinders were extensively utilized. In concept, these engines were not unlike the present-day automobile engine; a few of the in-line engines were air cooled. The rotary engine had cylinders arranged radially around a crankshaft; but unlike the modern radial engine, the crankshaft was fixed to the aircraft, and the cylinders and crankcase, with propeller attached, rotated around it. This engine type was relatively light and was cooled easily by engine rotation, advantages that accounted for its extensive use. The rotary engine, perfected in France, had a primitive control system and introduced undesirable gyroscopic moments in the aircraft that adversely affected flying characteristics. The rotary engine is a curiosity that rapidly vanished from the scene following the close of World War I.

The design of a successful aircraft, even today, is not an exact science. It involves a combination of proven scientific principles, engineering intuition, detailed market or mission requirements, and perhaps a bit of inventiveness and daring. Aircraft design during World War I was more inventive, intuitive, and daring than anything else. Pro-

totypes were frequently constructed from full-size chalk drawings laid out on the factory floor. The principles of aerodynamics that form so important a part of aircraft design today were relatively little understood by aircraft designers during the war. An indication of the state of the art in this area is given in the textbooks by Barnwell and Sayers published in 1917 (ref. 27) and by Klemin in 1918 (ref. 79). Structural design was haphazard, and stress analysis did not become an accepted part of the design process in many companies until midway through the World War. In an area of engineering in which structural strength, light weight, and aerodynamic efficiency are so important, it is indeed surprising that a number of relatively good aircraft were produced.

The evolution of the airplane during the turbulent years of World War I is described briefly in the following sections of this chapter. Fighter aircraft, which usually reflected the latest in design refinements, are considered first, after which consideration is given to heavy bombers and army cooperation aircraft.

Fighter Aircraft

A primary purpose of fighter aircraft is to destroy other aircraft, either in offensive or defensive modes of operation, or to pose such a compelling threat that enemy air operations are effectively curtailed. Enemy fighters, bombers, patrol and reconnaissance aircraft, as well as ground-support and transport aircraft, are the prey of the fighter. To perform its intended function, the fighter must be able to reach a favorable position for inflicting crippling damage on the enemy. This means that the fighter pilot must first be able to detect the enemy aircraft; the methods of detection employed in the First World War were primarily visual. Thus, the aircraft and pilot's position in it must be designed to provide the widest possible field of view. Detection means little, however, unless the aircraft possesses the performance and maneuverability necessary to achieve a favorable attack position and provides a steady gun platform together with sufficiently powerful armament to destroy the enemy once a favorable position has been achieved. Some of the performance and maneuverability characteristics of importance are speed in various flight conditions, rate of climb and ceiling, roll rate, turning radius and climb capability while in a turn, and range and endurance.

Sufficient strength must be provided for the aircraft to survive the loads imposed by high g maneuvers at high speed without structural failure. The ability to sustain a certain amount of enemy fire without

catastrophic damage is another important attribute of the successful fighter aircraft. Adding to the design challenge is the necessity for maintaining structural weight at a minimum, while at the same time providing the required strength and durability.

Another important ingredient inherent in a successful fighter aircraft is the manner in which it handles. The flying and handling characteristics of aircraft have been under study for over 60 years and continue to be the subject of investigation as new aircraft configurations evolve and new operating ranges of speed and altitude are encountered. Broadly speaking, an aircraft with good handling characteristics must obey the pilot's control inputs precisely, rapidly, and predictably without unwanted excursions or uncontrollable behavior and without excessive physical effort on the part of the pilot. Preferably, the aircraft should possess these desirable characteristics throughout its performance envelope. Further discussion of handling characteristics is contained in chapter 5.

The discussion above outlines in broad terms some of the more important characteristics of the successful fighter aircraft. These desirable characteristics have not changed very much over the years, although they have been more precisely defined. Also, the operating ranges of speed and altitude have changed, as have the weapons and the methods of detection. No aircraft has ever achieved perfection in all areas in terms of the state of the art available in a given time period. Aircraft design involves a compromise between many conflicting requirements. The successful fighter aircraft incorporates the proper blend of compromises that provides the characteristics necessary to counteract the enemy threat in a particular time period and combat environment. The evolution of this rather specialized type of aircraft in the hectic 4-year period of World War I is briefly described next. Discussed and illustrated are 11 fighters that operated over the Western front during this pioneer period of combat aircraft development.

Pioneer Fighters

The first true fighters to appear in World War I were the Fokker Eindecker series of monoplanes that caused a revolution in the concepts of the way in which a fighting airplane could be employed. The Eindecker was not particularly fast or maneuverable, but it was the first aircraft to effectively employ a fixed, forward-firing machine gun that was synchronized with the engine so that the bullets passed between

the blades of the revolving propeller. The gun was aimed by aiming the entire airplane. This new flying weapon entered combat service in the summer of 1915. Credit for the invention of the synchronized machine gun is a matter of debate among aviation historians, but there is no doubt that the Fokker Eindeckers were the first aircraft to employ this concept in an effective operational sense. Anthony Fokker's version of the invention of the synchronized machine gun and its early use are contained in his autobiography (ref. 50).

The results achieved with the Fokkers were spectacular, and the months during which these aircraft reigned supreme are often referred to as the era of the "Fokker Scourge"; Allied aircraft were sometimes called "Fokker Fodder." German pilots Oswald Boelcke and Max Immelmann became famous for flying this type of aircraft; Immelmann was killed in one as the result of structural failure in the air. It has never been established whether this failure was caused by enemy gunfire or a design defect.

The Eindecker series of aircraft appeared in four versions, E-I to E-IV, with the E-III type produced in the greatest numbers. They were similar in appearance and were equipped with one machine gun, except for the E-IV, which was larger, more powerful, and had two guns. Between 450 and 475 Eindeckers were manufactured.

Some of the characteristics of the E-III are given in table I (appendix A), and a photograph of a type E-IV is presented in figure 2.1. The photograph depicts a fragile-looking midwing monoplane, with the wings braced by an array of wires extending from a pylon mounted atop the fuselage to the wing and then down to a complex arrangement of struts that formed the landing gear. The wing itself was quite thin, a common engineering practice through most of the war years. Thick wings were thought, quite incorrectly, to produce prohibitively high drag. It is not known whether this mistaken notion arose because of results obtained from the very low Reynolds number wind tunnels available at that time; or because of poor airfoil design; or perhaps, because birds' wings were thin, designers therefore considered that shape to be the best. In any case, airfoil thickness ratios of 4 to 6 percent (ratio of airfoil thickness to wing chord) were the norm, and only the Germans successfully applied thick airfoils to wing design later in the war.

The control system employed on the Eindeckers was archaic even by 1914 standards. Lateral control was achieved by wing warping in a manner similar to that employed by the Wright brothers in 1903, and the vertical and horizontal tail units consisted of one-piece free-floating

Figure 2.1 — German Fokker E-IV Eindecker fighter; 1916. [ukn via Martin Copp]

surfaces. The stability and control characteristics of the aircraft were, of course, related to the floating angles of these surfaces as the angles of attack and sideslip of the aircraft varied. The characteristics of the aircraft and the effectiveness of the control system can be judged by the comments of a modern pilot who has flown a replica of the E-III. The late Frank Tallman in his book *Flying the Old Planes* (ref. 110) says ". . . the major flight characteristic ever present is the feeling that if you took your hands off the stick or your feet off of the rudders, the Eindecker would turn itself inside out or literally swap ends." He also indicates that the all-moving surfaces continually hunted back and forth with an attendant feedback into the pilot's hands and feet. These characteristics describe an aircraft that by modern standards would be considered unpleasant to fly, would be unlicensable, and certainly would inspire little confidence in the mind of the pilot.

The Eindecker was of conventional frame construction covered with fabric "doped" with glue to stretch it tight and to provide weatherproofing. The wing structure was of wood, whereas the fuselage frame departed from common practice in that it was constructed of welded steel tubing with wire bracing.

The E-III was powered with the 100-horsepower Oberursel rotary engine. One of these interesting and unique rotary-type engines is shown in figure 2.2. In order to limit centrifugal stresses, rotary en-

gines developed maximum power at relatively low rotational speeds, in the range of 1200 to 1400 revolutions per minute. The large diameter propeller on the Fokker E-IV shown in figure 2.1 was dictated by the low rotational speed of the engine. By modern standards, the engines of most World War I aircraft developed rated power at low rotational speed and utilized large diameter propellers. The propulsive efficiency was accordingly high at low speeds, which gave aircraft of that period good takeoff and climb characteristics.

A glance at the data in table I for the Fokker E-III indicates a rather light aircraft of 1342 pounds gross weight with a maximum speed of 87 miles per hour, a high zero-lift drag coefficient of 0.0771, and a low maximum lift-drag ratio of 6.4. Certainly these data do not suggest an aircraft of very impressive performance. Yet, the presence of an effective fixed, forward-firing, synchronized machine gun, which the Allied powers did not have, made the Eindecker the terror of the skies over the Western front in 1915 and secured for it an important place in the annals of World War I aviation history.

The German hold on air superiority was broken in the spring of 1916 by the appearance of several new British and French fighters that outclassed the Fokker Eindeckers. The British, who did not possess a satisfactory gun synchronizing gear, solved the problem of a forward-firing gun by a pragmatic, short-term configuration concept; the engine

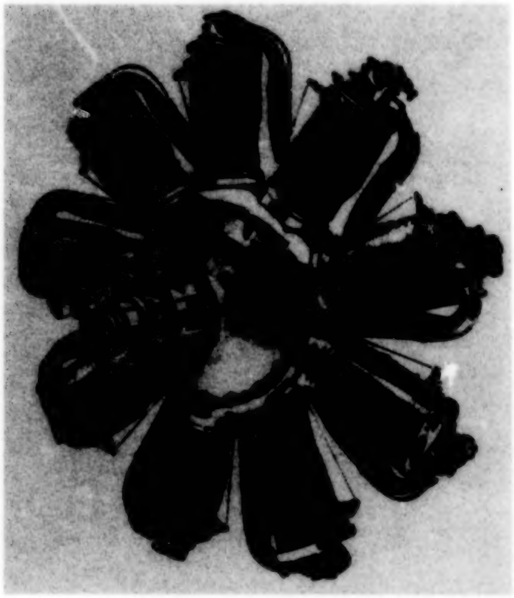

Figure 2.2—Nine-cylinder LeRhône rotary engine of 110 hp. [ukn]

and propeller were simply mounted behind the pilot, which allowed an unobstructed forward field of fire. Several pusher-type aircraft were developed. Typical of this design concept was the DeHavilland DH-2 shown in figure 2.3, designed by Geoffery DeHavilland for the Aircraft Manufacturing Company (AIRCO). The photograph depicts a strut-and-wire-braced, double-bay biplane employing thin, untapered wings. (A brief description of biplane terminology is contained in appendix D.) A small nacelle situated on the bottom wing contained the pilot's cockpit and gun in the forward portion and the 100-horsepower Gnome Monosoupape rotary engine in the pusher position in the rear. The horizontal and vertical tail surfaces were mounted behind the engine on an arrangement of four strut-and-wire-braced outriggers, or booms, which extended rearward from the wings. Cutouts in the trailing edges of the upper and lower wings provided clearance for the rotating propeller, which had four blades to minimize the extent of the cutouts and reduce the required spacing of the outriggers. The smaller diameter four-blade propeller, as compared with a two-blade propeller capable of absorbing the same power, also reduced the length of the landing gear.

Figure 2.3 — British DeHavilland DH-2 fighter; 1916. [National Archives via Martin Copp]

The pusher configuration arrangement of the DH-2 offered excellent visibility forward, upward, and downward to both sides, but a somewhat restricted view to the rear. Armament first consisted of a flexible, forward-firing gun or guns, but this was later replaced by a single fixed gun.

The biplane configuration employed on the DH-2, with detail design variations, was the most frequently used wing arrangements on World War I aircraft designs. The biplane design formula offered the best compromise between structural strength, light weight, and aerodynamic efficiency consistent with the state of the art. The British, as a matter of policy, were not interested in monoplanes because they had a reputation, perhaps undeserved, for structural weakness.

The DH-2 was of wooden frame construction covered with fabric, except for the top and forward parts of the nacelle, which were covered with plywood. Lateral control was provided by ailerons located on both the upper and lower wings, and the tail surfaces had both fixed and movable elements. According to reference 82, the aircraft was sensitive on the controls with a tendency to spin easily. Once they mastered it, however, pilots found the aircraft to be strong, maneuverable, and easy to fly.

A comparison of the data given in table I shows that the DH-2 was somewhat faster than the Fokker, was of greater aerodynamic efficiency, and had a significantly lower wing loading. The climbing capability of a fighter aircraft is a very important performance parameter, not shown by the data in table I. Curves showing the time required to climb to various altitudes, based on data given in reference 82, are presented in figure 2.18 for all the fighter aircraft discussed. The climb curves also give the DH-2 an edge over the Fokker. These advantages of the DH-2, together with control characteristics that were no doubt far superior to those of the Fokker, were responsible for the success of the "little pusher."

Major Leone G. Hawker, one of the early British aces, commanded the first Royal Flying Corps squadron equipped with the DH-2. While flying one of these aircraft, he was shot down by the German ace Baron von Richthofen flying an Albatros fighter. The DH-2 was a great success when introduced in the spring of 1916 but was outclassed by far superior German fighters by the time of Hawker's death in the late fall of 1916. The aircraft was belatedly withdrawn from combat in the summer of 1917. About 400 DH-2's were built.

One of the truly great fighter aircraft of the early war years was introduced to combat by the French in March 1916. The Nieuport 17, illustrated in figure 2.4, was a development of earlier Nieuport fighters and was extensively used not only by the French but by the British, Belgians, Italians, and Russians. After entering the war, the United States also employed the aircraft as a trainer. Many well-known Allied aces flew the Nieuport 17: Albert Ball and William Avery Bishop of the British Royal Flying Corps and René Fonck and Charles Nungesser of France exemplify aces who earned at least part of their reputation while flying the Nieuport 17. At the time the aircraft was introduced into combat, a satisfactory gun synchronizing gear was not available, but the deficiency was overcome by mounting a machine gun, which fired over the propeller arc, on the top of the upper wing. This arrangement is employed on the Nieuport 17 replica shown in figure 2.5. Subsequent versions of the aircraft employed the overwing gun in combination with a single synchronized gun firing between the propeller blades, or by a single synchronized gun alone. This later configuration is employed on the aircraft shown in figure 2.4.

Figure 2.4 — French Nieuport 17 fighter; 1916. [National Archives via Martin Copp]

The Nieuport 17 was a very neat, clean-looking, strut-and-wire-braced biplane powered by the 110-horsepower LeRhône 9J rotary engine. More properly, the configuration of the aircraft should be described as a sesquiplane since the lower wing is of much smaller chord than the upper one. The single-spar lower wing was connected to the upper wing of this single-bay biplane by V-type interplane struts. The small chord of the lower wing provided the pilot with excellent downward visibility, which is the most probable reason for the sesquiplane layout. In earlier Nieuport fighters, the small, single-spar lower wing had shown a tendency toward structural weakness; this deficiency was apparently corrected in the model 17. Lateral control was provided by ailerons on the upper wing only. The tail assembly consisted of an all-moving vertical surface, together with a fixed horizontal stabilizer equipped with a movable elevator. Construction was conventional wood framework covered with fabric, except for the tail which had a steel tube frame.

The data in table I indicate the Nieuport 17 to have been a light aircraft with a good weight-power ratio, low drag area, and high maxi-

Figure 2.5 — French Nieuport 17 with wing-mounted gun; 1916. [Peter C. Boisseau]

mum lift-drag ratio. The maximum speed was 107 miles per hour at 6500 feet. Comparing these characteristics, as well as the climb curves in figure 2.18, with those of the Fokker E-III and the DeHavilland DH-2 leaves little doubt of the superior qualities of the Nieuport 17. According to reference 23, this fighter was so well liked by the Allies that 317 of them were still in front-line service in August 1917—a long operational life for a combat aircraft in an era in which new aircraft were being developed in a matter of months.

The Two-Gun Fighter

High on the list of great fighter aircraft of the first world war is the name Albatros. Beginning with the introduction to combat of the model D-I in August 1916, Albatros fighters served in the German Air Force until the armistice in November 1918. Introduced in January 1917, the D-III and its refined variants the D-V and the D-Va were the best of the Albatros fighters and were produced in the greatest numbers. In November 1917, 446 D-III's and 556 D-V's and D-Va's were in service in combat squadrons with the German Air Force. Air superiority was again in Germany's hands from the late fall of 1916 until midsummer of 1917. So great was the carnage inflicted on Allied aircraft by German pilots flying Albatros fighters that April 1917 is still referred to by aviation historians as "Bloody April." Among the famous German aces who flew Albatros fighters were Manfred von Richthofen, Ernst Udet, Bruno Loerzer, and Werner Voss. Although the name of Richthofen is usually associated with the Fokker triplane, he scored most of his 80 victories flying Albatros fighters (ref. 96).

Two views of the Albatros D-III are shown in figures 2.6 and 2.7, and the characteristics of this version of the Albatros are given in table I. The D-III was a streamlined strut-and-wire-braced biplane that had V-type interplane struts connecting the small-chord lower wing to the upper wing. According to some sources, this arrangement was copied, at the insistence of the German Air Force, from the very successful Nieuport 17. Power was provided by a water-cooled, six-cylinder Mercedes engine of 160 horsepower. Not evident in the photographs is the airfoil-shaped cooling radiator located in the upper wing. Water feed and return pipes connecting the engine to the radiator can, however, be seen. Also not visible in the photographs are the two fixed, forward-facing machine guns synchronized to fire between the revolving blades of the propeller. The Albatros fighters were among the first biplanes to be armed in this way and may be thought of as setting a trend in fighter design which was to last for the next two decades. For example,

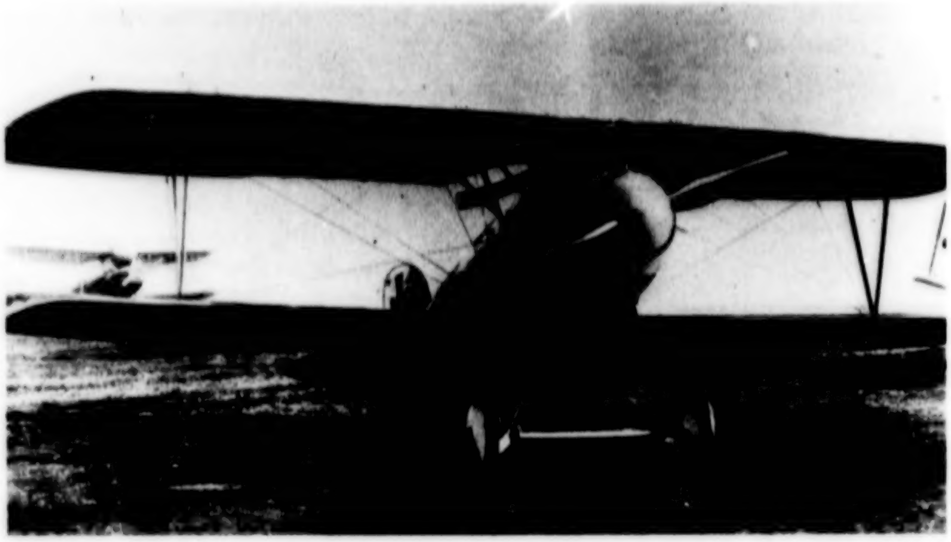

Figure 2.6 — German Albatros D-III fighter; 1917. [ukn via Martin Copp]

Figure 2.7 — Side view of prototype Albatros D-III fighter. [Peter M. Bowers via AAHS]

the U.S. Navy purchased its last biplane fighter with two forward-firing, synchronized guns in 1938.

The Albatros had several structural features worthy of mention. Of particular interest is the fuselage, which was of semimonocoque construction. The term "monocoque" comes from France and means single shell. Thus, the true monocoque fuselage consists of an outside shell, usually formed of plywood, which is held in shape by a number of transverse bulkheads contained within the shell. Louis Bechereau, a French designer, first employed plywood monocoque construction in the fuselage of the 1911 Deperdussion racing monoplane. A semimonocoque fuselage has, in addition to the transverse bulkheads, several longitudinal members to enhance the stability, stiffness, and strength of the structure. This type of construction was strong, rigid, fairly light in weight, and provided a smooth, streamlined shape. In addition, for a given outside diameter, a large usable internal fuselage diameter was available. The smooth, rounded shape of the fuselage of the D-III can be seen in figures 2.6 and 2.7. Interesting details of the semimonocoque type of construction, including many photographs, are given in reference 91. A number of other German aircraft manufacturers utilized this type of fuselage construction during the war years, and it will appear again on some of the racing aircraft of the 1920's (chapter 3) and on the high-performance Lockheed aircraft of the late twenties and early thirties (chapter 4).

The wings of the Albatros D-III were of conventional wood-frame construction covered with fabric. As in the Nieuport 17, the lower wing had only a single spar to which the V-type interplane struts were attached. The struts themselves were streamlined steel tubes. Throughout the life of the D-III, D-V, and D-Va designs, despite several modifications, the single-spar lower wing showed an inherent structural weakness that somewhat limited the performance of the aircraft. An examination of drawings of the lower wing (given in reference 91) shows that the single spar was located well behind the quarter-chord point (the approximate location of the aerodynamic center in the chordwise direction). This spar location suggests that the tendency of the wing to fail in high-speed dives was probably the result of aeroelastic divergence, a phenomenon apparently not understood at the time the Albatros fighters were developed. An increase in torsional stiffness or a relocation of the wing elastic axis, or a combination of both, is the usual cure for divergence. A brief description of aeroelastic divergence is given in the discussion of swept wings in chapter 10.

Control of the Albatros D–III was provided by ailerons on the upper wings and by an aerodynamically balanced rudder and elevator on the tail surfaces. The fixed portion of the vertical tail was covered with plywood and had elements above and below the fuselage. The tail skid formed an extension of the lower, or ventral, part of the fin. The fixed portion of the horizontal tail, like most aircraft of the period, was not adjustable and thus could not be used to trim the aircraft longitudinally while in flight. Accordingly, a constant push or pull on the control stick was necessary to maintain level flight at a constant speed and altitude. A rudimentary form of longitudinal "trim" system, consisting of a sliding collar on the control stick connected by a hinged link to the cockpit floor, was provided on the Albatros. A thumb-actuated set screw in the collar could be tightened, and the stick was then held in a fixed position; for brief periods, the pilot was then free to use both hands for other activities such as attempting to clear a jammed machine gun. The system is described and illustrated in reference 91. Information on the handling characteristics of the Albatros is limited, but what has been found indicates that it was easy to fly, with no dangerous characteristics.

A comparison of the data given in table I for the Albatros D–III and the Nieuport 17 leads to some interesting speculation. Although the D–III was heavier and had more wing area and a more powerful engine than the Nieuport, the values of the wing loading and the power loading for the two aircraft are not greatly different. Furthermore, the values of the zero-lift drag coefficient and the maximum lift-drag ratio are about the same. These two aircraft can therefore be considered to have about equal aerodynamic efficiency and, accordingly, to exhibit about the same performance characteristics. In fact, the maximum speeds given in table I are about the same although the altitudes at which the speeds were measured are somewhat different. Since, for small altitude variations, the decrease in drag that accompanies the reduction in air density is about offset by the reduction in power with altitude, the speed comparison of the two aircraft in the table is valid. Values of the time required to climb to various altitudes are also about the same for the two aircraft at the lower altitudes, as shown by the data in figure 2.18; however, the climbing capability of the Albatros is clearly superior to that of the Nieuport above 10 000 feet. This plus the heavier armament of the Albatros are no doubt responsible for the generally accepted opinion that it was a more effective fighter than the Nieuport 17.

The Triplane Phenomenon

Mention of World War I aviation evokes in the minds of many a vision of a brightly painted red triplane handled with consummate skill by the "Red Baron" as he closes for the kill of another Allied airplane. The triplane was, of course, the Fokker model Dr.-1, and the pilot was the great German ace Rittmeister Manfred Freiher von Richthofen. The Fokker Dr.-1 was a manifestation of a design phenomenon that swept the aircraft industry in the period 1917-18. During that time, no less than 34 triplane prototypes were constructed and test-flown in Germany (ref. 69). Other triplane prototypes were designed and tested by countries of the Allied Powers.

In today's terminology, all this triplane activity may be classified as an overreaction to the introduction in early 1917 of the British Sopwith triplane. This aircraft, in the hands of a few excellent pilots of the British Royal Naval Air Service, quickly made an enviable reputation as a formidable fighter. Raymond Collishaw was perhaps the best-known British pilot to fly the Sopwith triplane. Less than 75 of these aircraft were employed in combat operations; but so favorable were the reports of German pilots who had fought against the aircraft, as well as those of a few pilots including von Richthofen who had flown captured examples of the triplane, that the German government issued an invitation to industry for the submission of triplane prototypes for evaluation and indicated that production contracts would be forthcoming for deserving designs. Hence, the great triplane fad in Germany. Out of all this activity, the Fokker model Dr.-1 triplane was the only type produced in quantity; approximately 320 were ordered in the summer of 1917. The type was used in combat operations for about 1 year but was employed by a relatively few elite squadrons of the German Air Force.

A Fokker triplane replica is pictured in figure 2.8. The two wheels visible beneath the tail skid are not part of the aircraft but are attached to a dolly used for towing the aircraft on the ground. The Dr.-1 was a small, light machine equipped with a 110-horsepower rotary engine and, as indicated by the data in table I, had a gross weight of only 1290 pounds and a small upper wing of 23.7-foot span.

Although inspired by the Sopwith triplane, the Fokker Dr.-1 bore it no resemblance except for the three wings. The Sopwith employed a conventional strut-and-wire-braced wing arrangement, whereas the Fokker had no wire bracing between the wings and only a single strut connecting the lifting surfaces near the tips. These struts were intended to reduce wing vibration and flexing at high speed and did not materially contribute to the static strength of the structure. Interestingly,

Figure 2.8 — German Fokker Dr.-1 triplane fighter; 1917. [author's collection]

the first Fokker triplane flew without any interplane struts at all. The wings themselves were cantilever; that is, they obtained their strength entirely from internal bracing.

The radical departure of the Fokker Dr.-1 structure from contemporary aircraft design concepts was made possible by the use of wing airfoil sections much thicker than usual at the time. The mistaken notion that low wing drag could only be obtained with thin airfoil sections has been mentioned previously. The Fokker triplane and subsequent Fokker designs proved the incorrectness of the thin wing concept. The Göttingen 298 airfoil section of 13-percent thickness ratio, employed on the Dr.-1, is shown in figure 2.9 in comparison with three thin airfoils of the World War I period. These sections were of 4- to 5-percent thickness ratio.

The wing structure of the Fokker Dr.-1 consisted of two closely spaced box spars connected at the top and bottom with plywood sheets; the resulting torque box provided great strength and stiffness. The ribs were made of plywood with lightening holes and shear braces, and the leading edges were partially covered with plywood back to the front spar. The entire wing, including the plywood leading edge, was covered with fabric. In common with many World War I aircraft, the trailing edge of the wing was formed from wire and usually assumed a

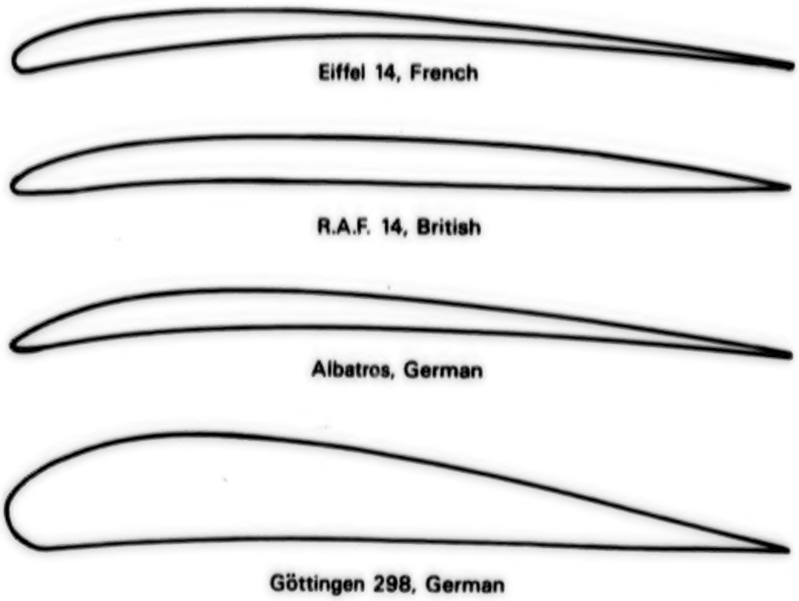

Figure 2.9 — Four examples of airfoil sections employed in wings of World War I airplanes.

scalloped appearance after the fabric had been tightened with dope. Following standard Fokker practice, the fuselage, tail surfaces, and ailerons were constructed of welded steel tubing. Illustrative drawings of the structural details of the Dr.-1 are given in reference 69.

Large horn-balanced ailerons were employed only on the upper wing of the Fokker Dr.-1. The planform of this wing, including the ailerons, is shown in figure 2.10 in comparison with upper wing planform shapes of several of the other aircraft discussed here. The horn balance on the Dr.-1 wing is that portion of the aileron that extends outboard of the wing tip and forward of the aileron hinge line. The purpose of the balances, sometimes informally referred to as "elephant ears," was to reduce the aileron hinge moments, and thus the force that the pilot had to exert on the control stick to roll the aircraft. According to reference 72, the "raked" tips of the other planforms shown in the figure might be expected to have a small beneficial effect on the drag associated with the production of lift.

The horizontal tail of the Fokker Dr.-1 consisted of a fixed stabilizer with large horn-balanced elevators. The vertical tail was an all-moving unit, without a fixed fin, and was similar in design to that of the Fokker E-III. Other features to note in figure 2.8 are the skids

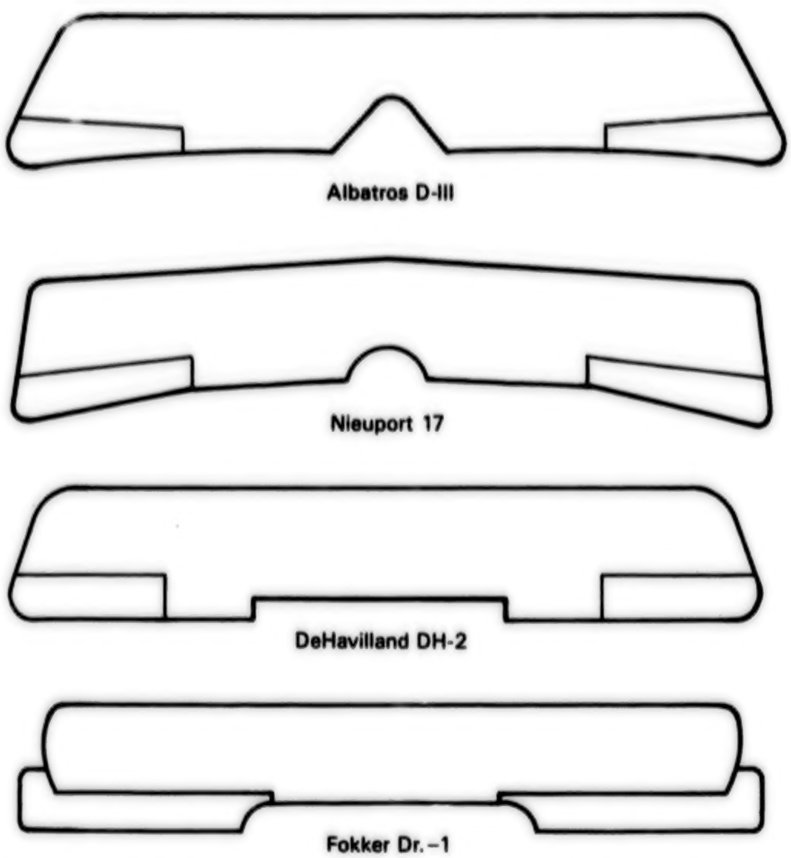

Figure 2.10 — Wing-planform shapes of four World War I fighter airplanes.

under the tips of the lower wings and the small winglike fairing that enclosed the axle between the wheels of the landing gear. This fairing became something of a trademark on many later Fokker aircraft.

The zero-lift drag coefficient of 0.0323 given in table I for the Fokker Dr.-1 was among the lowest of any of the World War I fighter aircraft analyzed, as was the drag area of 6.69 square feet. The maximum lift-drag ratio was a correspondingly high 8.0. The low zero-lift drag coefficient of the Fokker triplane was no doubt due in part to the relatively small surface area of the fuselage in relation to that of the wings. Another important ingredient contributing to the low drag of the aircraft was the absence of the multitude of bracing wires found between the wings on most other aircraft of that period. These wires, or cables, were often of round cross-sectional shape. On the basis of the drag coefficients given in reference 72, the drag in pounds of a

smooth, 0.25-inch-diameter wire at the speeds of World War I aircraft is the same as that of a strut of the same length having a 25-inch chord and an airfoil section of 10- or 12-percent thickness ratio. The wires, intended to take only loads in tension, were, of course, lighter than struts designed for the same purpose. The gain in efficiency associated with a design from which the wires are eliminated is obvious. A good description of the interplane bracing cables employed on the Albatros D–Va is given in reference 91.

The speed of 103 miles per hour at 13 120 feet was not particularly high (table I); most discussions of the Fokker Dr.-1 in the literature indicate that the aircraft was slow but was highly maneuverable and had an outstandingly high rate of climb. The time-to-climb curves in figure 2.18 indicate a climb performance for the Dr.–1 that was far superior to that of the Albatros D–III and the Nieuport 17; in fact, it had a better rate of climb (indicated by the slope of the curve) than any of the other aircraft up to an altitude of between 8000 and 10 000 feet. Unfortunately, these data, taken from reference 82, cannot be considered conclusive since data from other sources, for example reference 119, show much higher times to climb than indicated in figure 2.18. Two sets of climb data are given in reference 69; one set is in essential agreement with the data of figure 2.18, whereas the other is similar to that in reference 119. In an attempt to resolve this discrepancy, the sea-level rates of climb for the Dr.–1 were estimated for several different weights with the use of the methods given in chapter 6 of reference 90. The calculations showed that the climb data in figure 2.18 might have been achievable with a light fuel load, but not with full fuel tanks. The aircraft weight for which the climb data of reference 82 apply is not known for any of the aircraft. The superior climbing capability of the Dr.–1 must be attributed to the thick airfoil sections that allowed operation at the high lift coefficients required for optimum climbing performance, not to the use of three wings instead of two.

The triplane fighter of World War I must be considered as something of an aberration in the course of aeronautical development. The design trade-offs and reasoning underlying the concept of such an aircraft are nowhere adequately explained in any of the reference documents. However, one might speculate along the following lines: For a given wing span and area, the effective aspect ratio (related to the drag associated with the production of lift) of a triplane is higher than that of a biplane or monoplane (ref. 103). Or, for a given aspect ratio, the span of a triplane can be less than that of a biplane or monoplane of the same wing area. Thus, the rolling inertia of the triplane can be less

than that of a biplane or monoplane. Greater maneuverability might, therefore, be obtainable with a triplane configuration. Further, the triplane allows the wing area to be divided among three relatively narrow-chord wings, which may be arranged relative to the aircraft center of gravity in such a way as to provide the pilot with better visibility than could be achieved with a comparable biplane. Finally, for a given level of longitudinal stability, the physical distance between the wings and the tail may be reduced on a triplane as compared with a biplane.

The quantitative theoretical relationships between the drag-due-to-lift of monoplanes, biplanes, and triplanes were not available in 1916; however, as indicated by references 27 and 79, empirical design data together with qualitative theoretical ideas were available in the literature. The possible and perhaps nebulous advantages of the triplane, however, could not prevail against the increased complication and cost of constructing three wings instead of two and later, when monoplanes were better understood, one.

In any event, the Fokker triplane will remain an integral part of World War I aviation lore and will be discussed as long as that era is of interest. And inextricably interwoven with the Fokker triplane story is the name of the highest scoring ace of World War I — the legendary Baron von Richthofen.

Fighters in 1918

Discussed next are four fighter aircraft that served with distinction in front-line combat operations until the termination of hostilities in November 1918. Three of these aircraft, the French SPAD XIII and the British Sopwith Camel and Dolphin, were strut-and-wire-braced biplanes that had a conventional wood-frame structure covered with fabric. The fourth, the German Fokker D-VII biplane, had internally braced cantilever wings like the Fokker triplane, together with a typical Fokker welded steel tube fuselage.

Sopwith Camel

The Sopwith Camel evolved from the earlier Sopwith Pup and, as can be seen in figure 2.11, was an awkward-looking single-bay biplane powered with a rotary engine. It was the first British fighter with two forward-firing, synchronized machine guns. A small metal fairing cov-

Figure 2.11 — British Sopwith F.1 Camel fighter; 1917. [William T. Larkins via AAHS]

ered a portion of the guns, which gave the fuselage a humped appearance when viewed from the side. This hump coupled with the large dihedral angle of the lower wing and the flat upper wing are allegedly responsible for the name "Camel." The aircraft first began combat operations in July 1917 and was a front-line combat aircraft until the armistice in November 1918. Camels accounted for the destruction of more enemy aircraft than any other Allied fighter of the war — a total of 1294. Production of the Camel amounted to 5490 aircraft.

The flat upper wing of the Camel was dictated by a desire for production simplicity. The original intention was to construct the wing in one piece, although in production it was made in three pieces. The dihedral of the lower wing was accordingly made sufficiently large to compensate for the flat upper wing. The Camel utilized a relatively new innovation in wing-bracing wires. From a study of references 100 and 110 and an examination of detailed drawings of the Sopwith Dolphin, streamline wires were used for bracing on both the Camel and the Dolphin. (Streamline wires have a cross-sectional shape much like a symmetrical airfoil section.) Such wires were developed by the Royal Air-

craft Factory at Farnborough, England and were first flown experimentally on the SE–4 in 1914 (ref. 39). The Sopwith Pup and triplane, both of which entered service in 1916, also had streamline bracing wires. The advantage in drag reduction of using this type of wire rather than the usual round wire is great; there is a factor of about 10 between the drag coefficients of the two types of wire. Yet, no significant use was made of this improved type of wire during the war except by British aircraft manufacturers. Because streamline wire was first developed at Farnborough, it was known as Rafwire.

The Camel was produced with a number of different power plants of varying horsepower; the greatest number of aircraft, however, had the Clerget 9B nine-cylinder rotary engine of 130 horsepower. Characteristics of the Sopwith F.1 Camel equipped with this engine are given in table I.

The Camel was a small, relatively light aircraft with a gross weight of only 1482 pounds. Its maximum speed of 105 miles per hour at 10 000 feet was not particularly fast, and its zero-lift drag coefficient and maximum lift-drag ratio do not suggest a very outstanding aircraft. The climb data given in figure 2.18 show that the Camel performed better than the Albatros D–III, but not so well as some of the other aircraft for which data are shown.

All the reference literature, however, credit the Camel with having superb maneuverability. Some of the agility displayed by the Camel is usually attributed to the Sopwith practice of locating the concentrated weights in the aircraft—pilot, engine, guns, and fuel—in close proximity to each other. Thus in the Camel the pilot's feet were beneath the rear components of the engine, the guns were over his legs, and the fuel tank was immediately behind his back in the fuselage. Some idea of the bunching together of these elements around the pilot is suggested by figure 2.12, where a present-day pilot is shown sitting in the cockpit of a Sopwith Camel replica. Certainly, the pilot was not seated in a very favorable position to withstand the effects of a serious crash.

In the hands of a skillful pilot, the Camel was a formidable weapon. Unfortunately, the flying careers of many mediocre or student pilots were ended abruptly and fatally as a result of the bizarre handling characteristics of the aircraft. In combination with the aerodynamic characteristics of the aircraft itself, the torque and gyroscopic moments associated with the heavy rotating engine gave an incredibly fast turning capability but, at the same time, were responsible for the peculiar handling characteristics of the aircraft. The confusing way in which the controls had to be manipulated in left- and right-hand turns

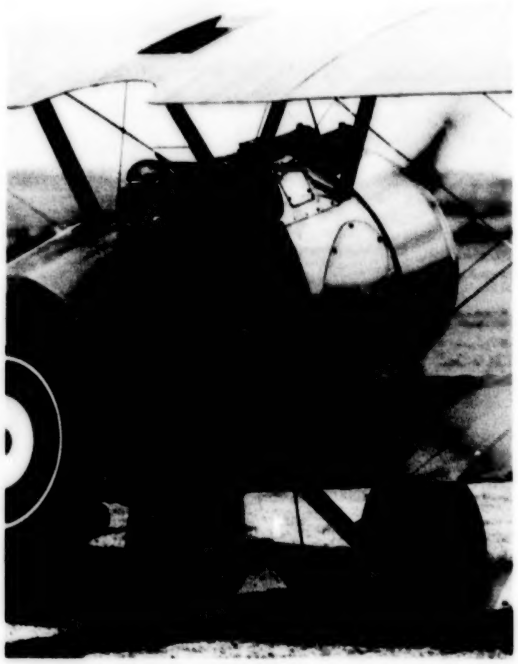

Figure 2.12—Pilot in cockpit of a replica Sopwith Camel. [Flt. Intl.]

provides an example of these characteristics. Based on the information contained in appendix II of reference 100 for the later Sopwith Snipe, the gyroscopic action of the engine caused a nose-up moment in a left turn and a nose-down moment in a right turn. Accordingly, left stick, a large amount of left rudder, and moderate back stick were required in a steep left turn; too much back stick caused the aircraft to stall and spin. Right stick, a moderate amount of *left* rudder, and full back stick were required in a steep right turn. There seems little doubt that these odd control techniques could cause confusion and indecision on the part of an inexperienced pilot.

The Sopwith Camel has been called the most loved and the most hated aircraft of World War I, loved by those who mastered it and exploited its peculiarities and hated by those who did not. The outstanding dogfighting capability of the Camel together with the record number of German aircraft it destroyed give it an honored place in the World War I aircraft hall of fame. If this were not enough, one version of von Richthofen's last fight has a relatively obscure Canadian ace, Captain A. Roy Brown, shooting down the famous baron while flying . . . a Sopwith Camel.

SPAD XIII

SPAD was the acronym of the French aircraft company Societé pour Aviation et les Derieves, headed by famed aviation pioneer Louis Bleriot, which produced a line of highly successful fighter aircraft in World War I. The SPAD model XIII C.1 is the subject of the following discussion.

The SPAD XIII descended from the earlier model VII which first entered combat in the fall of 1916. In contrast to the earlier aircraft, the model XIII was somewhat larger, had a more powerful engine, and was equipped with two synchronized machine guns rather than one. It entered combat in the fall of 1917 and served with the air forces of most of the Allied Nations, including the United States. Many famous aces flew the SPAD, but to Americans the best known was Captain Edward V. Rickenbacker, the top scoring U.S. ace of the First World War. A SPAD XIII in the markings of the 94th Pursuit Squadron of the American Expeditionary Force is shown in figure 2.13; the officer shown is Captain Rickenbacker.

Figure 2.13 — French SPAD XIII C.1 fighter; 1917. Captain Edward V. Rickenbacker is in front of the airplane. [USAF]

Figure 2.13 depicts a stubby but graceful-looking biplane with wings of equal chord and span, configured with no stagger and relatively small gap. The small gap in combination with the center cutout of the upper wing gave the pilot excellent visibility over the top of the wing. The design appears to be that of a double-bay biplane; however, the inner struts served only to stabilize the rather long wing-bracing wires and prevent their flapping and chaffing (ref. 22). The wires themselves consisted of round cables. The cockpit was close behind the engine with the pilot's feet and part of his legs located in aluminum tunnels beneath the engine (ref. 110). The landing gear was positioned well forward, ahead of the center of gravity, to minimize the risk of a nose-over on landing. Ailerons were on the upper wing only, and, as with the other aircraft described, no means of longitudinal trim was provided.

The SPAD XIII was powered with the Hispano-Suiza 8BA engine of 220 horsepower. The engine had eight water-cooled cylinders in two banks of four arranged in a V-type configuration, much like that of many modern automobile engines. The distinctive round radiator, equipped with manually operated (from the cockpit) shutters for controlling the cooling airflow, may be seen in figure 2.13. Long exhaust pipes ran on either side of the fuselage and terminated behind the pilot's cockpit. This arrangement resulted in a relatively quiet environment for the pilot (ref. 110). In an interesting survey of aircraft piston engine development, Taylor (ref. 111) credits the Hispano-Suiza with being one of the best and most advanced engines of World War I, as well as one that served as a sort of progenitor for a long line of Curtiss and Rolls-Royce liquid-cooled engines that culminated in the Rolls-Royce Merlin of World War II.

The data in table I indicate that the SPAD XIII had the most favorable power loading of any of the aircraft considered and a high (for its day) wing loading. These characteristics coupled with a relatively low zero-lift drag coefficient and low drag area gave the SPAD the highest speed of any of the aircraft listed in the table. As shown by the data in figure 2.18, the climb characteristics of the SPAD were bettered only by three of the Fokker aircraft.

The reference literature suggests that the SPAD XIII was not as maneuverable as some of the other fighters, but its high performance, great strength, and multigun armament made it a highly effective weapon. Its ability to dive steeply for prolonged periods of time without fear of structural failure is emphasized in all the reference material.

Piloting the aircraft required care, particularly at low speeds, and the use of moderate amounts of power was recommended in landing.

Although the SPAD XIII incorporated no new technical innovations, it synergistically combined an airframe of relatively high aerodynamic efficiency and great structural strength with an excellent engine to produce an outstanding aircraft. It may be regarded as representative of the top of the state of the art of a 1918 fighter aircraft equipped with thin, strut-and-wire-braced wings. The SPAD was so highly regarded that a number of countries maintained the aircraft as part of their active air force inventory for several years following the war. A total of 8472 SPAD XIII aircraft were manufactured.

Fokker D-VII

In the early 1970's, the U.S. Air Force announced with much fanfare a flyoff competition between prototypes of a new lightweight fighter aircraft. The resulting competition involved several years of research, engineering, and detailed flight evaluation before a winner was announced, the General Dynamics F-16. There was no novelty about the Air Force's prototype competition; it is a time-honored method of selecting military aircraft. The date of the first such competition is unknown, but one of the most renowned of German World War I fighters, the Fokker D-VII, was selected for full-scale production after being chosen the winner from about 30 competing prototypes. The time was late January 1918, and the place was Aldershof Airfield near Berlin.

As an indication of the speed with which prototype fighter aircraft could be developed at that time, Fokker alone entered no less than nine different types. Each of the competing aircraft was demonstrated by the manufacturer and then evaluated by well-known front-line pilots. The Fokker D-VII was the unanimous winner of the competition and first entered combat in April 1918 — an indication of the rapidity with which the unsophisticated aircraft of that era could be developed from prototype to combat readiness. Over 800 model D-VII aircraft were in front-line operations by mid-August 1918.

The Fokker D-VII is illustrated in figure 2.14 and, as can be seen, was a squarish-looking biplane equipped with an in-line engine and an automobile-type radiator located in the nose. The most advanced feature of the aircraft was the use of internally braced cantilever wings that had thick airfoil sections and a wooden structure similar to that previously described for the Fokker triplane. The thick wings were re-

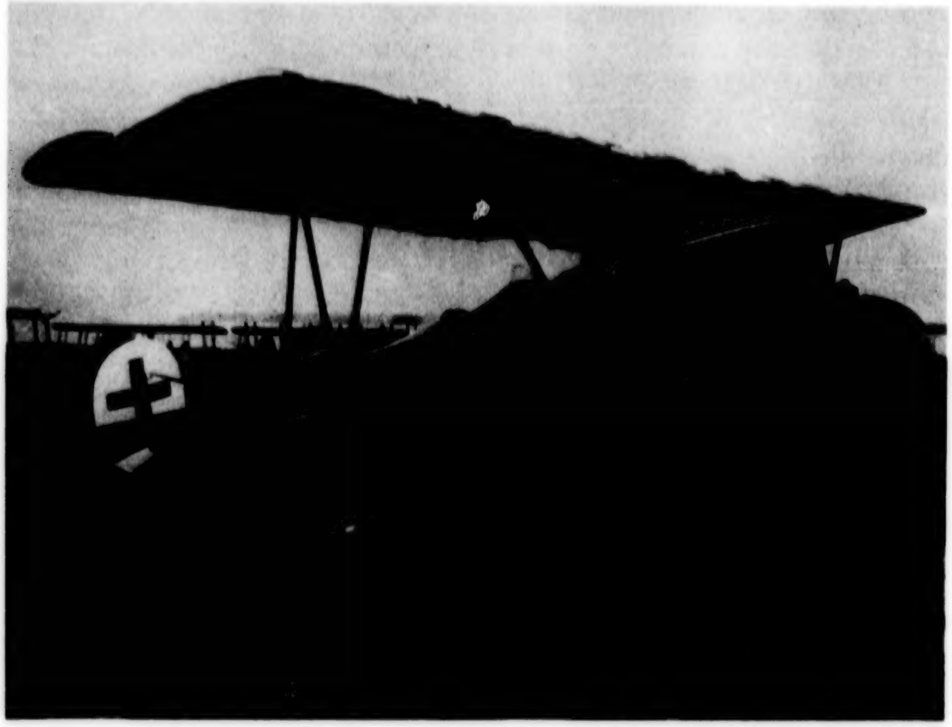

Figure 2.14 — German Fokker D-VII fighter; 1918. [Merle Omstead via Martin Copp]

sponsible for many of the fine characteristics of the aircraft. The ailerons, located on the upper wing only, as well as the elevator and rudder had horn balances to reduce control forces. The winglike fairing between the wheels is also evident in figure 2.14; one experimental version of the D-VII had a fuel tank located in this fairing to reduce the fire hazard. The production aircraft was powered with either a Mercedes 160-horsepower engine or a BMW 185-horsepower engine. Both engines were six-cylinder, in-line, water-cooled types. The BMW was the preferred engine, however, as the aircraft proved to be somewhat underpowered when equipped with the Mercedes (ref. 112).

The Fokker D-VII was the heaviest of the fighters considered here and had wing loading and power loading values greater than those of the SPAD XIII. The power loading was in fact no lower than that of the Sopwith Camel, and the wing loading was higher. On the basis of these comparisons, the climb performance of the D-VII might be expected, according to the relationships given in chapter 6 of reference

90, to be inferior to that of both the SPAD XIII and the Sopwith Camel. On the contrary, the data in figure 2.18 show the D-VII to have much better climb performance then either of the other two aircraft. Brief calculations of the sea-level rate of climb by the methods in reference 90 indicate that the climb data for the Fokker D-VII are reasonable but that the SPAD should have had much better climb performance than indicated in figure 2.18. The explanation can no doubt be attributed, as mentioned for the triplane, to the thicker airfoil sections employed in the wings of the D-VII. The climb analysis showed that the maximum rate of climb could be achieved at lift coefficients of about 1.1 and 1.0 for the Fokker and the SPAD, respectively. The thick-wing D-VII could probably be flown with comfort at the required lift coefficient for maximum rate of climb, whereas the SPAD most likely could not. In fact, a lift coefficient of 1.0 might have been beyond the maximum value achievable by the SPAD XIII with its thin wings.

In other respects, the performance of the Fokker D-VII was good but not outstanding. The maximum speed of 124 miles per hour was not as high as that of the SPAD. This would be expected since the ratio of power-to-drag area was lower for the Fokker. The value of the maximum lift-drag ratio of the D-VII, however, was about 10 percent higher than that of the SPAD, which can be attributed to the higher aspect ratio of the Fokker wing configuration.

Not expressed by the data in table I were the superb handling characteristics that all the reference documents attribute to the Fokker D-VII. The aircraft was highly responsive, with light control forces; yet, unlike the Camel, it had no vices or contrary tendencies, and it could be flown with confidence throughout its flight envelope. Hence, the aircraft could be handled competently and safely by relatively inexperienced pilots and superbly by experienced ones. Frank Tallman clearly regarded the D-VII as the most outstanding of the World War I fighter aircraft he had the opportunity to fly (ref. 110).

Perhaps the greatest tribute to the D-VII can be found in article IV of the armistice agreement, which lists war material to be handed over to the Allies and specifically mentions all aircraft of the D-VII type — the only aircraft to be specifically cited in the armistice agreement. Certainly, this was a strong endorsement of the capabilities of the young Dutch designer, test pilot, and entrepreneur Anthony Herman Gerard Fokker, who provided the German Air Force with so many excellent aircraft . . . after being told by the Allied Powers that his services were not wanted (ref. 50).

Sopwith Dolphin

Unlike the SPAD XIII and the Fokker D-VII, the Sopwith Dolphin cannot be regarded as one of the great fighter aircraft of World War I, but it is included here as an illustration of one of the many unusual designs developed during that turbulent era. The aircraft is shown in figure 2.15. At first glance, the Dolphin appears to be a conventional double-bay biplane equipped with an in-line engine. A closer look, however, discloses that the wings are configured in an unorthodox fashion, with the lower wing located ahead of the upper wing. An aircraft with this wing arrangement is described as having negative stagger. The earlier DeHavilland DH-5 (a limited success) had this wing arrangement, as did the well-known Beech model 17 which appeared about 15 years after the Dolphin. (See chapter 4.)

The wing arrangement of the Dolphin was dictated solely by a desire to give the pilot improved visibility in the forward, upward, and rearward directions. Following the usual Sopwith practice of locating the concentrated masses in close proximity to each other, the pilot was positioned immediately behind the eight-cylinder Hispano-Suiza engine, with his feet actually resting on the rudder bar beneath the rear part of the crankcase. As in the Camel, the fuel tank was in the fuselage immediately behind the cockpit. To overcome the poor visibility of the Camel, the top wing of the Dolphin was located close to the fuselage so that the pilot's head protruded through a large cutout in the wing near the leading edge; this cutout can be seen in figure 2.15. Positioning the aerodynamic center in the proper relation to the aircraft center of gravity made it necessary to place the lower wing ahead of the upper wing, which was located relatively far back from the nose. The negative stagger configuration was the result.

The wing configuration of the Dolphin undoubtedly gave the pilot excellent visibility but held certain undesirable pitfalls as well. Should the aircraft turn onto its back in an accident, the entire weight of the aircraft might come to rest on the top of his head. Should he be able to duck his head in time to avoid this unpleasant possibility, the proximity of the upper wing to the fuselage, together with the cabane struts and wires on either side of the cockpit, effectively trapped him in the aircraft between a large engine in front and a fuel tank in back. As if this were not enough, the butts of the two forward-firing, synchronized machine guns protruded into the cockpit and, in addition, one or two semiflexible guns were usually mounted on the leading edge of the wing and fired at angles of 45° or more over the propeller. These guns also

Figure 2.15 — British Sopwith 5F.1 Dolphin fighter; 1918. [ukn via Martin Copp]

protruded into the cockpit. (The flexible guns are not mounted on the aircraft shown in figure 2.15.) Understandably, pilots were not entirely happy when posted to squadrons equipped with the Dolphin. Various methods of protecting the pilot in case of an accident, including "roll bars," were investigated, but no such device was universally incorporated on production aircraft.

The first prototype Dolphin had a radiator located in front of the engine, automobile style, but this installation greatly restricted visibility in landing. The single nose radiator was then replaced with two small radiators located on either side of the fuselage, just to the rear of the cockpit. These radiators can be seen in figure 2.15. The pipes connecting the radiators to the engine passed through the cockpit on each side. One Dolphin pilot described how the pipes were used as "hand warmers" during flight at high altitudes. While the control stick was held with one hand, the other glove-encased hand grasped the water pipe until it was warm, after which the pilot flew the aircraft with the warm hand while holding the pipe on the opposite side of the cockpit with his other hand (so said the late Charles E. Walton, formerly of No. 23 Squadron of the Royal Air Force, in conversation with the author). Such a story becomes believable in view of the temperatures of 0° F and below encountered at altitudes of 15 000 feet and above, even on a warm summer day.

According to the data given in table I, the Dolphin was a large, heavy fighter with a gross weight of 1911 pounds and a wing area of 263 square feet. The maximum speed was a very credible 128 miles per hour at 10 000 feet but was somewhat less that that of the SPAD. The climb results in figure 2.18 show a performance improvement of the Dolphin at the higher altitudes, as compared with the Camel, but the Dolphin was inferior at all altitudes to the SPAD XIII and the Fokker D-VII. Most references to the Dolphin allude to its excellent high-altitude capability, but the results shown do not support this contention. Data in reference 31, however, show a much improved climb capability when later versions of the aircraft were equipped with a more powerful 300-horsepower engine. The flying qualities of the aircraft apparently had no treacherous tendencies but were characterized by fairly heavy control forces and relatively slow response.

The Dolphin first flew in June 1917 and entered combat in squadron strength in January 1918. A total of 2150 Dolphins were ordered, but only 1532 were delivered by the end of the war. Not many combat squadrons were equipped with the aircraft. That the Dolphin was thought well of is indicated by the expressed intention of the French to build under license a 300-horsepower version of the aircraft for use by their air force.

Reappearance of the Monoplane Fighter

The German Air Force sponsored another flyoff fighter competition at Aldershof in June 1918. Twelve companies entered 25 prototypes; of these, 5 were Fokker monoplanes. The Fokker D-VIII monoplane was the overall winner, and a production order was placed for 400 of them. A second aircraft, the Junkers D-I, also received a limited production contract. Both of these aircraft arrived on the scene too late to make any sort of reputation in combat, but both are included in the present discussion because of their technical significance. The Fokker D-VIII and the Junkers D-I are shown in figures 2.16 and 2.17, respectively.

The configuration of the Fokker D-VIII is known as a parasol monoplane. This type is characterized by a single wing supported above the fuselage by an arrangement of cabane struts and has the advantage of giving the pilot good downward visibility, as compared with a midwing or low-wing design, but has the disadvantage of the drag-producing cabane struts. Like the wings of the Fokker D-VII and the Fokker triplane, the thick wing of the D-VIII was internally braced and

Figure 2.16 — German Fokker D-VIII fighter; 1918. [USAF via Martin Copp]

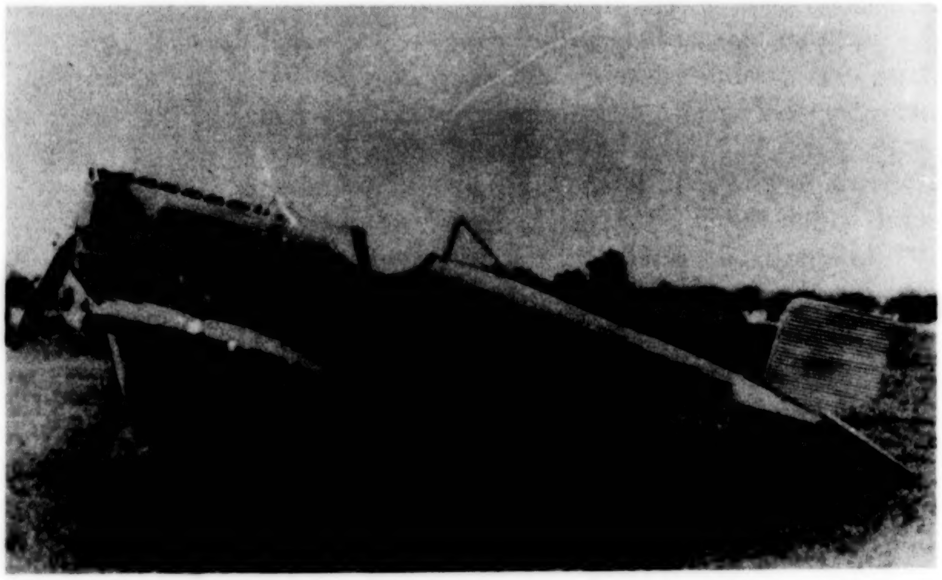

Figure 2.17—German Junkers D-I all-metal fighter; 1918. [ukn via Martin Copp]

full cantilever. Unlike the earlier aircraft, however, the D-VIII wing was covered entirely with plywood, which gave it great strength and rigidity. Also, it was one of the few wings of the World War I period to be tapered in both planform and thickness ratio. Wing taper not only increases aerodynamic efficiency but also structural efficiency, especially for a cantilever wing, since taper reduces the wing weight and root-bending stress for a given wing area. Wing damping in roll is also reduced by wing taper; this means a higher rate of roll for a given aileron-supplied rolling moment. The D-VIII wing, scaled to various sizes, was used on Fokker aircraft for many years (ref. 38).

The fuselage and tail structure were of typical Fokker design and consisted of welded steel frames covered with fabric. Power was supplied by an Oberursel rotary engine of 110 horsepower, which was the same engine that powered the earlier Fokker triplane. At 1238 pounds, the gross weight of the D-VIII was slightly less than that of the triplane and about the same as that of the Nieuport 17.

The maximum speed of the D-VIII was a modest 114 miles per hour at 6500 feet, but the climbing capability of the aircraft, shown by the data in figure 2.18, was outstanding. As discussed in connection with the triplane and the D-VII, the superb climbing performance of the D-VIII was due in large measure to the thick airfoil sections utilized in the wing. The small wing area with respect to the fuselage and tail area is partly responsible for the high zero-lift drag coefficient of 0.0552. Other important contributors to the high drag coefficient are the complex arrangement of cabane struts, fixed landing gear with large unstreamlined wheels, and open cockpit. Truly low drag coefficients can only be achieved when, in addition to cantilever wings, all these other drag-producing elements are eliminated and very careful attention is given to detailed design and refinement. This synergistic combination was finally achieved in the time period between 1930 and 1940. (See chapter 4.) To put the drag coefficient of the D-VIII in perspective, the value of this coefficient for a modern general aviation aircraft, the Beech Bonanza, is 0.0192.

Although the Fokker D-VIII is of technical interest because of its wing design, the data do not seem to indicate that the aircraft represented any significant improvement over the D-VII. The 145-horsepower Oberursel rotary engine was intended as a replacement for the 110-horsepower unit but was not manufactured in sufficient quantity to allow its use on production aircraft. Flight tests of an experimental model of the D-VIII equipped with the larger engine showed much better performance than indicated by the data in table I.

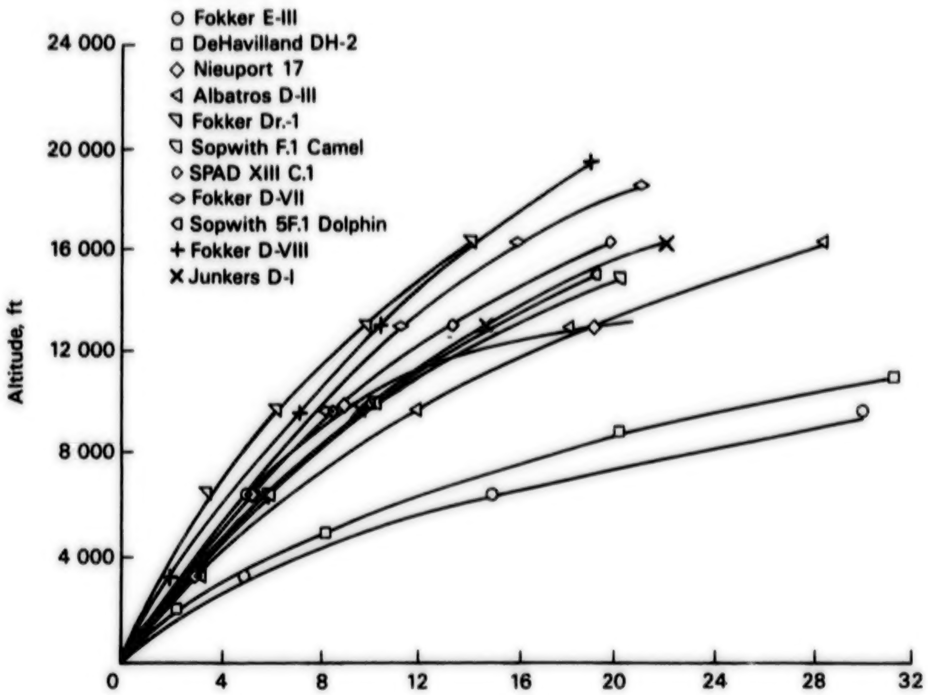

Figure 2.18 — Time required to climb to various altitudes for 11 World War I fighters. [data from ref. 82]

No discussion of the Fokker D–VIII would be complete without mention of the structural problem encountered with the wing. Some 20 aircraft were delivered in late July 1918, but in a fairly short time, several were lost in flight as a result of structural failure of the wings. Although some disagreement as to the cause of these failures can be found in the literature, the account given by Fokker in his autobiography (ref. 50) seems reasonable. According to his account, the technical department of the German Air Force required that the rear wing spar of the production aircraft be strengthened to conform with design rules established for aircraft with conventional strut-and-wire-braced wings. In modern terminology, the elastic axis of the cantilever wing (the chordwise location of the axis about which the wing twists) was moved rearward, with the result that the wing diverged, or twisted off, at a certain critical speed that varied with altitude. (See chapter 10.) Once the wing design reverted to the original rear spar size, the elastic axis

was moved forward and no further difficulty was encountered. Wing divergence and flutter are well understood today but were something of a mystery for many years. An understanding of these phenomena is particularly important in the design of structurally sound cantilever wings. Such wings were regarded with grave suspicion for a long time because of problems such as those encountered with the D-VIII and other aircraft having cantilever wings. The Fokker D-VIII returned to combat operations in October 1918, and 85 were in use at the time of the armistice. A total of 381 examples of the aircraft, known informally as the Flying Razor, were delivered.

The configuration of the Junkers D-I monoplane fighter (fig. 2.17) was modern in appearance and featured a thick, full cantilever wing mounted in the low position at the bottom of the fuselage. Although not apparent in the photograph, the wing tapered in thickness ratio from approximately 17 percent at the root to about 12 percent at the tip, but was untapered in planform. The airfoil thickness ratio at the root was greater than that of any of the airfoil sections employed on the Fokker fighters. Other features to note on the aircraft are the 185-horsepower BMW engine with nose-mounted radiator, the all-moving vertical tail, and the roll bar located behind the cockpit to protect the pilot's head if the aircraft nosed over onto its back.

The most interesting aspect of the D-I was its all-metal structure. Professor Hugo Junkers was an early advocate of all-metal aircraft structures; the D-I was one of his early successful monoplane designs. The internal structure was made up of riveted aluminum alloy tubing that was covered with corrugated sheets of the same material. Most of the strength resided in the internal structure, with the corrugations in the covering providing local panel stiffness; the torsional stiffness of the wings was also enhanced by the metal covering. The type of construction employed in the D-I was relatively heavy but had great durability and was used in the design of many Junkers aircraft until well into the 1930's. In the United States, the famous Ford trimotor employed the Junkers type of structural design. (See chapter 4.)

The durability of the all-metal structure was one of its most attractive attributes. The types of cloth with dope finishes used on most World War I aircraft deteriorated rapidly, apparently a result of light of certain wave lengths in the Sun's spectrum. A great deal of study was given to finding means for protecting aircraft covering. Certain types of dope or paint were found to offer more protection from the Sun than others (ref. 39). Wooden wings, such as employed on the D-VIII and later Fokker designs, were subject to delamination, rot, and deteriora-

tion of glue joints. All these factors highlighted the advantages of all-metal construction, although the strut-and-wire-braced biplane covered with fabric continued, at that time, to give the lightest weight for a given strength.

The Junkers D-I had a relatively high zero-lift drag coefficient of 0.0612, due in part to reasons similar to those outlined for the Fokker D-VIII. In addition, the corrugations in the covering increased the wetted area (the surface area exposed to the airstream) by 20 to 40 percent (ref. 72); this increase is not accounted for in the conventional method of defining the drag coefficient. The maximum lift-drag ratio was a poor 7.0, which compares quite unfavorably with the value of 8.1 for the Fokker models D-VII and D-VIII, and 9.2 for the Sopwith Dolphin. The maximum speed quoted for the D-I varies from 115 to 149 miles per hour depending upon the reference consulted. A value of 119 miles per hour is listed here and is thought to be close to the maximum speed achieved. The climbing performance of the aircraft was about the same as that of the Sopwith Dolphin. The advantages of the thick wing apparently could not overcome the disadvantages of the high wing loading, high power loading, and the high zero-lift drag coefficient.

Forty-one Junkers D-I fighters were built, but apparently none saw combat service.

Fighter Progress, 1914–18

By the end of World War I, the fighter airplane had progressed from a flimsy, low-performance, and clumsy vehicle to a highly effective aircraft. Many configuration types were tried in combat, but the strut-and-wire-braced biplane equipped with two synchronized machine guns firing between the rotating propeller blades set a pattern in fighter design that lasted until the mid-1930's. Although the thick cantilever wing was successfully employed by Fokker, the concept was not widely used until the monoplane fighter became the standard configuration type just prior to World War II.

Engine power and reliability increased during the World War I period, as did aircraft structural strength and reliability. Detailed aircraft stress analysis, unusual in 1914, had become common design practice by 1918, and a fairly comprehensive body of aerodynamic data was available to the designer. Aircraft control and handling characteristics, though largely a matter of cut-and-try experimentation, also greatly improved during the 4-year period.

Aircraft performance improvements can easily be shown in a quantitative way by graphical means. The large improvements in climbing performance have already been discussed with the use of the time-to-climb curves given in figure 2.18. A more favorable relationship between the wing loading and power loading together with higher aerodynamic efficiency were responsible for much of the improved climb performance realized from 1914 to 1918. The importance of the thick airfoil sections employed by Fokker and Junkers in allowing the aircraft to climb at its optimum lift coefficient has also been indicated.

The trend in speed capability is shown in figure 2.19, in which the maximum speed V_{max} is plotted against the power parameter $\bar{H}$, which is the cube root of the ratio of engine power to drag area (ref. 90). Since the speeds in table I are not all specified at the same altitude, the parameter $\bar{H}$ contains an adjustment for the effect of altitude on drag and maximum available power as follows:

$$\bar{H} = \sqrt[3]{\frac{P_0}{f}\left(\frac{\gamma}{\sigma}\right)}$$

where P_0 is the maximum power available at sea level, f is the drag area, σ is the atmospheric density ratio for the given altitude, and γ is the percentage of maximum sea-level power available at that altitude. The values of both σ and γ were obtained from reference 90.

The method of presenting the speed data assumes that the drag due to lift is a small fraction of the total drag for the maximum-speed flight condition and that the propeller efficiency is about the same for the different aircraft. The near linear correlation of the data in figure 2.19 shows these to be good assumptions in most cases. In the 4-year period of World War I, the maximum speed of fighter aircraft increased from 87 to 134 miles per hour — or expressed another way, the maximum speed increased by 54 percent. This increase in achievable maximum speed resulted from a reduction in drag area, that is, more efficient aerodynamic design, and from increased engine power.

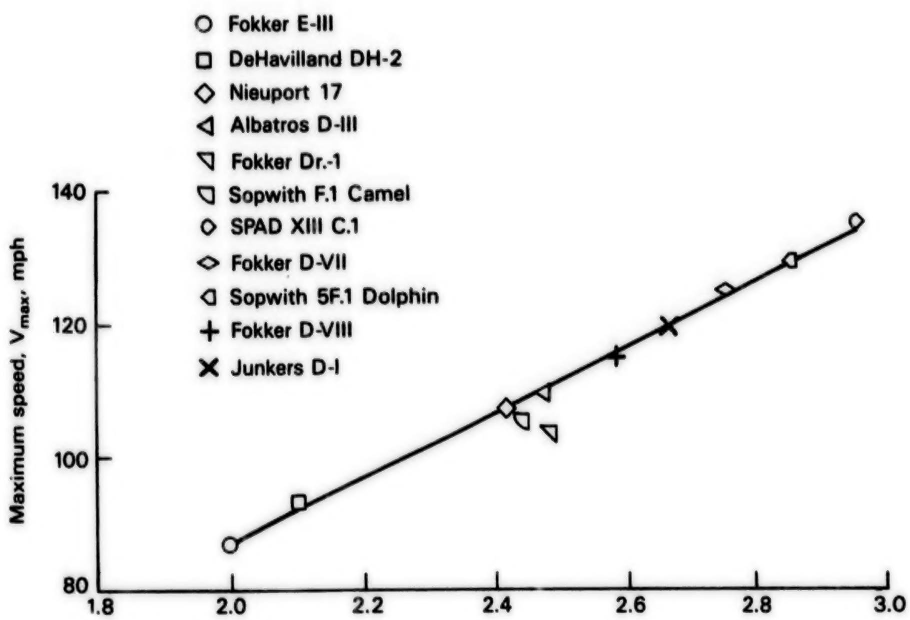

Figure 2.19 — Variation of maximum speed with power parameter H.

For example, numerical values for the Fokker E–III and the SPAD XIII, based on data from table I, illustrate the point as follows:

Aircraft	P_0	f	$\overline{H}$[a]
Fokker E–III	100	12.61	1.99
SPAD XIII C.1	220	8.33	2.98

[a] For sea-level conditions.

In comparing the values of the two aircraft, the SPAD has over twice the power but only 65 percent of the drag area of the Fokker. The quest for high performance has always been exemplified by vigorous efforts to increase both aerodynamic efficiency and power. For example, the drag area and power of the World War II North American P–51 fighter (chapter 5) were 3.75 square feet and 1490 horsepower, respectively. The corresponding value of $\overline{H}$ was 7.35. Compare these numbers with those for the Fokker and the SPAD!

Aircraft structural efficiency is also of great interest and can be thought of in terms of the minimum weight structure needed to meet required strength and stiffness criteria. Simple methods of adequately illustrating trends in structural efficiency are difficult to define. One fairly simple but relatively crude approach was presented by Wilson in reference 122 and was later used in reference 90. Correlations in reference 122, augmented by the present writer with a great deal of new data, show that the sum of the weights of the payload, fuel, and propulsion system tends to be nearly a constant fraction of the gross weight in well-designed aircraft regardless of the method of construction or era in which the aircraft was designed. Put another way, the useful load fraction $1-(W_e/W_g)$ should correlate closely with the engine weight fraction W_t/W_g, where W_g is the gross weight, W_e is the empty weight, and W_t is the propulsion-system weight.

The useful load fraction is plotted as a function of the engine weight fraction in figure 2.20 for the 11 fighter aircraft discussed in this chapter. The empty and gross weights are given in table I; the engine weights are based on data contained in reference 24. The dry engine weights given in reference 24 for the water-cooled engines were

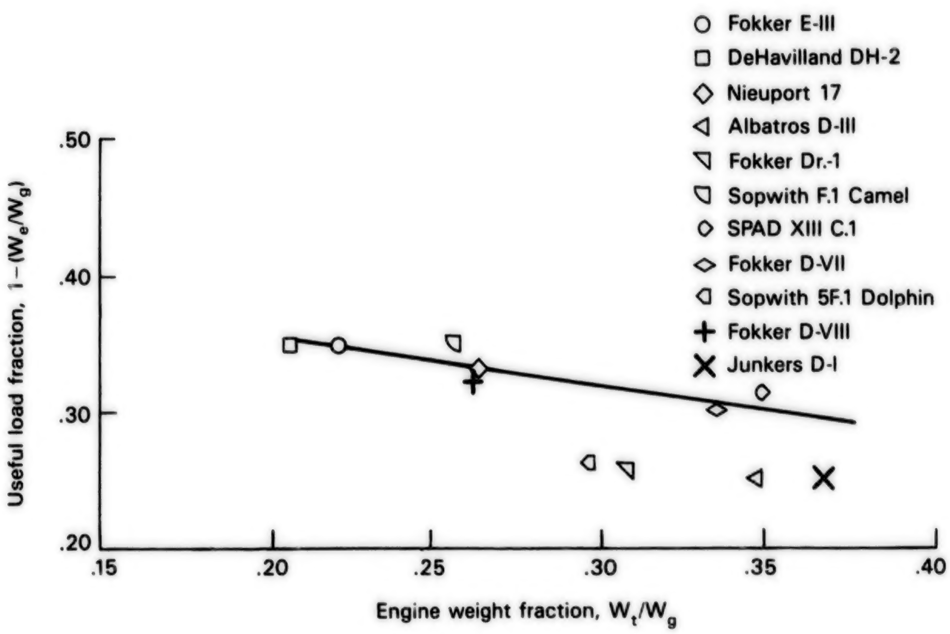

Figure 2.20 — Aircraft useful load fraction as function of engine weight fraction.

increased by 10 percent to account for the weight of the radiator and associated plumbing system and the cooling water.

Seven of the aircraft show a close correlation between the useful load and engine weight fractions. A relatively consistent level of structural efficiency is accordingly suggested. Four of the aircraft, however, show values of the useful load fraction significantly below the straight-line fairing through the data for the other aircraft. The four aircraft with reduced structural efficiency were the all-metal Junkers D–1, the Albatros D–III with its semimonocoque wooden fuselage, the Fokker Dr.–1 with its three wings, and the Sopwith Dolphin. The reduced values of useful load fraction are perhaps explainable by unique features incorporated in three of these aircraft, but there seems to be no clear reasons for the high empty weight of the Sopwith Dolphin.

This discussion of design and performance trends concludes the section on World War I fighter aircraft. Attention is now focused on multiengine bombers of that era.

Heavy Bombers

Most types of World War I aircraft, including fighters, were used at one time or another for tactical or ground-support bombing operations. The heavy bombers discussed in this section are what would be called strategic bombers in present-day terminology. They were used for bombing such targets as docks and harbor installations, rail yards, factories, and cities. The mission of these aircraft required them to have sufficient radius of action and payload capability to deliver a significant bomb load on a variety of targets and to carry enough defensive armament to offer a reasonable probability of mission success and safe return to base. Heavy bombers were used singly and in formations of several aircraft, on both day and night missions. Speed, maneuverability, and rate of climb were of secondary importance although a high ceiling was considered desirable.

The mission requirements for heavy bombers led to large, heavy (for that time period) multiengine aircraft just as they do today. Gross weights varied widely but usually fell in the range from 8000 to 16 000 pounds, and some of the German special-purpose R-planes weighed over 30 000 pounds (ref. 68). Two engines were used on most designs, although examples can be found of aircraft with three, four, and five engines. Most of the aircraft were multibay strut-and-wire-braced biplanes; however, several triplanes appeared, one of which is described

herein. At war's end, there were several German designs for highly advanced monoplane bombers that incorporated thick, cantilever wings (ref. 68). Construction of most heavy bombers consisted of a conventional wood framework covered with fabric.

The first of the large, heavy bombers was the Sikorsky Ilya Muromets, which first flew in February 1914. Caproni, Gotha, Friedrichshafen, A.E.G., Handley Page, and Vickers are a few other names that will be forever linked with the large, heavy bombers of the World War I era. Three heavy bombers, the German Gotha G.IV, the British Handley Page 0/400, and the Italian Caproni CA.42 are discussed here to give a glimpse of the size and characteristics of this class of aircraft.

Gotha G.IV

The name Gotha still evokes in the minds of some people the terrifying image of a group of large aircraft dropping bombs on the helpless citizens of a great metropolitan area. The Gotha gained this dubious distinction because of its use in the bombing raids on London in 1917 and 1918. Twenty-seven Gotha attacks were made in the course of about a year. Not a large application of strategic air power by World War II standards but enough to cause great consternation in an era when the English Channel was still mistakenly thought to ensure protection of the British Isles against a foreign invader. The Gotha raids, conducted first in daylight and later at night, actually caused little physical damage, but the psychological impact was such that badly needed British squadrons were recalled from the front to protect Britain against the German invader. Actually, several types of German aircraft participated in the bombing of London, but the name Gotha has for some reasons become synonymous with the bombing of helpless cities.

The Gotha model G.IV depicted in figure 2.21 was a triple-bay biplane equipped with two pusher-type engines mounted between the upper and lower wings, one on either side of the fuselage. The thin wings incorporated a small amount of sweepback to position the aerodynamic center in proper relation to the aircraft center of gravity. Horn balances were employed on the ailerons and rudder to reduce the control forces required to maneuver this very large aircraft. The landing gear had four main wheels; two were positioned below the bottom wing at the location of each engine nacelle.

The Gotha G.IV was manned by a crew of three: a single pilot and two gunners. The front gunner armed with a flexible machine gun was

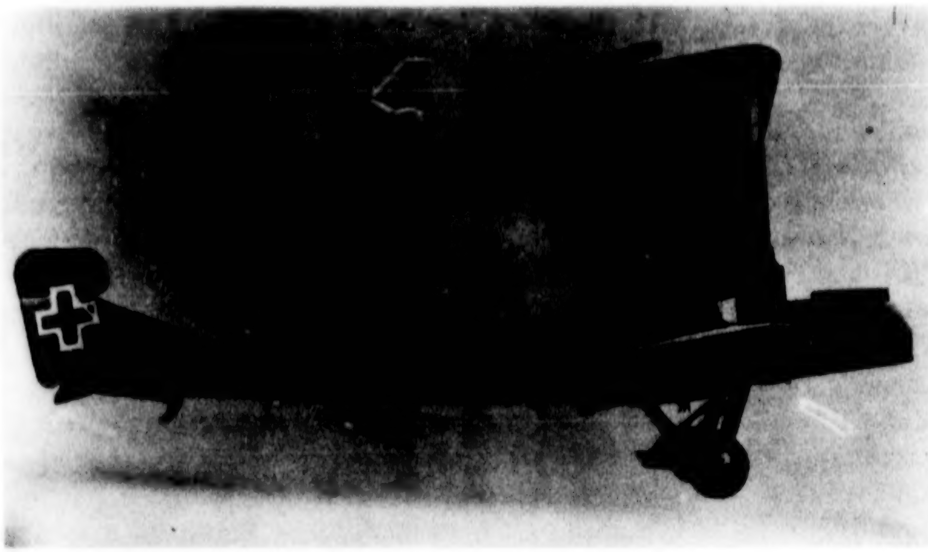

Figure 2.21 — German Gotha G.IV twin-engine bomber; 1917. [ukn via Martin Copp]

located in an open cockpit at the nose of the aircraft; this man also served as the bombardier. Behind the front gunner and just ahead of the upper wing was the pilot's cockpit. His flight controls consisted of the usual rudder bar and stick, but a "steering wheel," like that in an automobile, was mounted at the top of the stick and was used for deflecting the ailerons. The use of a full wheel, rather than a yoke as in modern aircraft, suggests that several revolutions of the wheel were required to move the ailerons through their full range of deflection. Aircraft response to control inputs must have been sluggish, and the piloting job must have seemed something like a wrestling match. The third crew member was another gunner located in an open cockpit behind the upper wing. His flexible machine gun could be utilized effectively in various quadrants above and to the sides of the aircraft and could also be fired downward and rearward through a sort of inclined tunnel that passed through the inside of the fuselage and opened on the bottom. The rear gunner could accordingly fire, through a limited angular range, at an aircraft attacking from below and to the rear. This feature proved to be a startling and unwelcome discovery to a number of unsuspecting Allied pilots.

The performance of the 8558-pound gross weight Gotha was not spectacular, as can be seen from the data in table I for the slightly im-

proved Gotha G.V. The maximum speed was only 87 miles per hour, which suggests a cruising speed at 75-percent power of about 78 miles per hour. This cruising speed, coupled with an estimated stalling speed of 56 miles per hour gave the pilot a very narrow speed corridor in which to fly and maneuver the aircraft. The maximum lift-drag ratio of 7.7 seems reasonably high for an aircraft festooned with so many struts, wires, wheels, and other protuberances. The usual load of the Gotha on a London raid consisted of six 110-pound bombs carried externally.

The reference sources indicate that more Gothas were lost in flying accidents than in combat with the enemy. Sluggish response to control inputs together with its narrow speed corridor may have contributed to the high accident rate. Many accidents occurred in landing. The fuselage was reportedly weak, probably because of the gun tunnel, and frequently broke in half on a hard landing.

All in all, the Gotha does not seem to have been the superb aircraft that its fearsome reputation would suggest. The reality, as with so many other aircraft, does not live up to the legend.

Handley Page 0/400

Like the Gotha G.IV, the Handley Page 0/400 illustrated in figure 2.22 was a multibay biplane equipped with two engines mounted between the wings and with a four-wheel main landing gear; two wheels were mounted below the lower wing at the location of each of the engine nacelles. The appearance of the British Handley Page bomber, however, was startlingly different from that of the German Gotha. The large gap between the wings, marked wing dihedral angle, and large span of the upper wing as compared with the lower are distinctive features in the appearance of the aircraft. Also in marked contrast to the pusher engine arrangement of the Gotha, the 0/400 employed a tractor configuration. Another distinctive feature, not evident in the photograph, is the tail assembly, which consisted of two horizontal surfaces arranged in a biplane configuration. A single fixed fin, centrally located between the two horizontal surfaces, and two all-moving rudders, also located between the horizontal surfaces but positioned near the tips, comprised the vertical tail surfaces. Horn-balanced ailerons and elevators were utilized to reduce control forces.

The wings folded rearward, just outboard of the engines, to a position parallel to the fuselage. This complication was dictated by a requirement that the aircraft fit into a standard-size Royal Air Force

Figure 2.22 — British Handley Page 0/400 twin-engine bomber; 1916–17. [USAF via Martin Copp]

hangar. Apparently, the authorities responsible for aircraft procurement thought it more cost effective to complicate and perhaps compromise the aircraft than to build new hangars.

The crew of the Handley Page 0/400 usually consisted of four men. A gunner-bombardier, located in the nose of the aircraft, had two flexible machine guns. The two pilots were in an open cockpit behind the front gunner and just ahead of the upper wing; each pilot had a complete set of flight controls. The necessity for two pilots is suggested by the 9-hour flight maximum duration of the aircraft. The second gunner was located in a cockpit behind the upper wing and, as in the case of the front gunner, was provided with two flexible machine guns. In addition, a single flexible machine gun was mounted on the floor inside the fuselage and could be fired downward and rearward through a small trap door in the bottom of the fuselage. Apparently, the single rear gunner was expected to alternate between this gun and the two top-mounted guns, depending upon the position of the attacker. The frustration the single rear gunner must have felt in the event of a simultaneous attack from above and below can readily be imagined.

Surely, a second rear gunner must have been carried on missions in which aggressive attack by many enemy aircraft was anticipated.

The gross weight of the Handley Page was 14 425 pounds (table I), nearly 6000 pounds heavier than the Gotha, and the wing area was 1655 square feet as compared with 963 square feet for the German bomber. The maximum lift-drag ratio of the 0/400 was a very impressive 9.7, which was a full 26 percent higher than that of the Gotha. The Handley Page also had the higher top speed of the two aircraft. The 0/400 was large enough and had sufficient fuel capacity to deliver a 2000-pound bomb load on a target located 300 miles from home base and return safely. The bombs themselves were carried inside the fuselage in a vertical position ready for release. The Handley Page 0/400 seems to have been an outstanding aircraft for its time and, in most respects, superior to the Gotha except for its service ceiling of 8500 feet, which was less than half that attributed to the Gotha.

The size and certain other characteristics of the Handley Page 0/400 can be put in perspective by comparison with more modern aircraft. The wing loading and power loading of 8.7 and 20.5 are fairly close to the corresponding values of 6.9 and 18 for the famous Piper J-3 Cub (chapter 4), and the values of the maximum lift-drag ratio of the two aircraft are nearly the same. Thus, in a sense, the 0/400 can be likened to a 14 000-pound Cub, although the response to control inputs and the control forces required of the pilot must be considered as utterly different for the two aircraft. Cecil Lewis in reference 85 suggests the handling characteristics of the aircraft in the following quotation: "True, it was like a lorry in the air. When you decided to turn left, you pushed over the controls, went and had a cup of tea and came back to find the turn just starting."

Another interesting comparison of the Handley Page can be made with the modern-day Boeing 727–200 jet airliner (chapter 13). The wing areas of the two aircraft are almost the same, but the 727 is nearly 15 times as heavy as the Handley Page, is about 7 times as fast, and has a value of the maximum lift-drag ratio more than twice that of the 0/400. All these changes occurred in a time span of a little less than 50 years.

The first Handley Page bomber was flown in 1915, and the 0/400 version appeared in 1916. About 800 Handley Page bombers of all types were built during the war. The model 0/400 continued in military service for several years after the war, and several were converted for use as civil transports. The 0/400 was scheduled for large-scale production in the United States for use by the American Expeditionary

Force in France. By the time hostilities ceased in November 1918, only 107 examples had been completed and all production contracts were soon terminated.

The principal legacy of the Gotha and Handley Page heavy bombers was the twin-engine, strut-and-wire-braced, open-cockpit biplane configuration that dominated bomber development for many years following the end of World War I. Various models of the Keystone bomber were employed by the U.S. Army Air Corps until the mid-1930's. These aircraft incorporated the same configuration concepts as the Gotha and Handley Page, with fewer struts and wires, more powerful engines, better structures, and marginally better performance.

Caproni CA.42

The name Caproni is an honored one in the annals of World War I aviation. The Italian firm bearing that name, along with Sikorsky in Russia, first flew heavy multiengine bombers in the year 1913, and Caproni bombers were used throughout World War I, not only by Italy but by England and France as well. Production of one version of a Caproni bomber was also planned in the United States but had not materialized at war's end.

All Caproni bombers had three engines. Two of these were mounted in a tractor arrangement, with one engine at the nose of each of two fuselagelike booms that connected the wings and tail assembly. The third engine was a pusher installed in the rear of a nacelle situated between the wings. Pilot and gunner-bombardier were in cockpits ahead of the pusher engine. The rear gunner(s) was located in several different positions in the various Caproni bomber designs. Both biplane and triplane bombers were built by Caproni, with the number of biplanes produced far outnumbering the triplanes. About 200 Caproni bombers of all types were manufactured, of which about 30 were triplanes. In Italian service, these aircraft were extensively used for bombing targets in the Austro-Hungarian empire. Such raids originated in Italy and required round-trip flights across the Alps. Good high-altitude performance was accordingly an important design requirement.

Although production of Caproni biplanes far outnumbered the triplanes, the model CA.42 triplane bomber was selected for inclusion here because it represents an interesting application of the triplane formula to a very large aircraft. Some of the reasons for selecting a triplane configuration were given in the previous section describing the

Fokker Dr.-1 triplane fighter. For a very large airplane in which the physical dimensions are limited, perhaps by hanger size or tiedown area on the airfield, the triplane arrangement offers a higher effective aspect ratio for a given wing span and area than does a biplane. The triplane arrangement of the CA.42 probably derives from this argument since the aircraft had a very large wing area.

The Caproni CA.42 may be seen in figure 2.23 and offers a unique, if somewhat grotesque, appearance. The three wings were connected and braced by a veritable forest of struts and wires. A front view of the aircraft shows that the interplane struts were configured in a five-bay arrangement. The center nacelle containing the pusher engine, pilot, and forward gunner was attached to the undersurface of the center wing. The tips of the pusher propeller can be seen above and below the left fuselage-boom. A rear gunner was positioned in each fuselage-boom immediately behind the center wing. The boxlike pod on the lower wing housed the bombs. The main landing gear consisted of

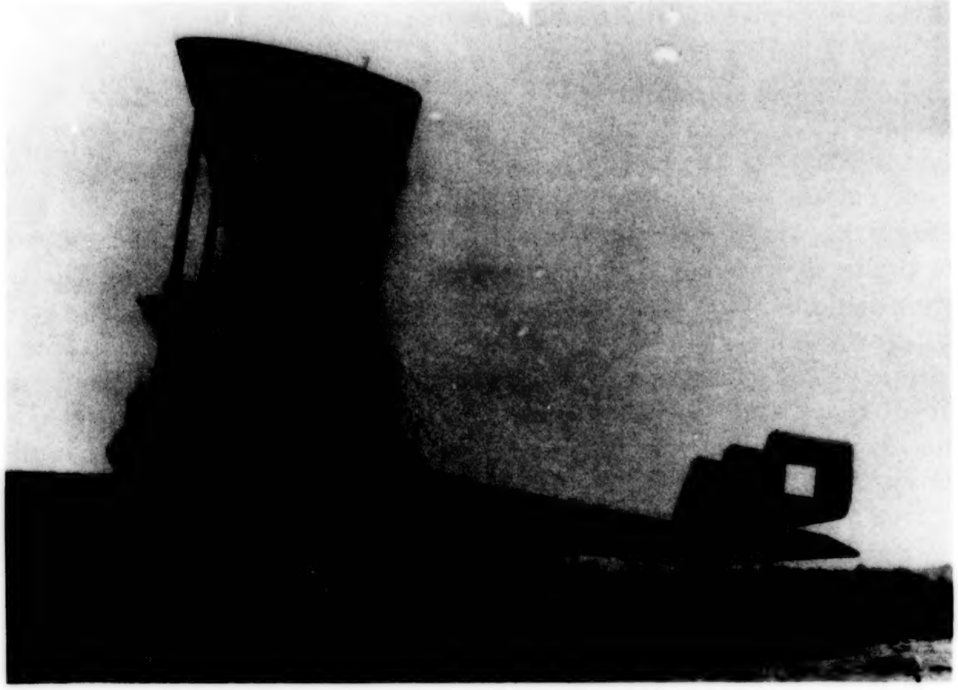

Figure 2.23 — Italian Caproni CA.42 three-engine triplane bomber; 1917. [Stephen J. Hudek via Martin Copp]

eight wheels in two clusters of four each, skids were located under each wing tip, and rather tall tail skids were at the rear. The large number of wheels was intended to distribute the weight of the aircraft on the ground and thus prevent the aircraft from becoming mired in the relatively soft turf airfields in use at that time. Three rudders were mounted on a single horizontal tail; a later version of the aircraft had a biplane horizontal-tail configuration. Ailerons were employed on all three wings.

A number of sources were consulted in assembling the data given in table I. Although the various sources were in essential agreement on the dimensions of the CA.42, discrepancies were found in the weight and performance data. Engines of different power were employed on a number of the production aircraft and may account for the confusion in the data. The specifications in table I were taken from reference 1 and are for the aircraft equipped with U.S.-built Liberty engines of 400 horsepower each. At 17 700 pounds gross weight, the CA.42 is the heaviest of the aircraft considered, and the maximum speed of 98 miles per hour is higher than that of either the Gotha or the Handley Page 0/400. The lower wing loading and more favorable ratio of power to weight, as compared with the other two bombers, probably gave it a good high-altitude capability for transalpine flying. One reference gives a flight duration of 7 hours and a maximum bomb load of 3200 pounds. Assuming a cruising speed of 89 miles per hour at 75-percent power, the CA.42 had an estimated range of about 600 miles, or the ability to deliver its bombs on a target 300 miles from home base and return safely.

The Caproni CA.42 seems to have had a very creditable performance when equipped with Liberty engines; with lower power engines, the performance was not nearly so good. Perhaps the appearance of the Liberty engine relatively late in the war contributed to the small number of aircraft built. In one reference the aircraft was stated to be difficult to fly, but no specific details are given.

At least three CA.42 triplane bombers were sent to the United States for evaluation. One of these was to have been tested at Langley Field, Virginia, but was completely destroyed in a crash at Langley on its maiden flight in December 1917.

With this brief glimpse of the heavy bomber in World War I, attention is now focused on the two-seat army cooperation and light bomber types that constituted the workhorse aircraft of that era.

Army Cooperation Aircraft

The unglamorous two-seat aircraft, working in cooperation with army ground forces, formed the backbone of aerial activity in World War I and undoubtedly contributed more to military successes than any other class of aircraft. One of the primary functions of the much-heralded single-seat fighters was the protection of their own two-seaters and the destruction of those belonging to the enemy. Army cooperation aircraft performed a variety of diverse duties including photoreconnaissance, artillery spotting, observation of enemy troop movements, ground strafing, and daylight tactical bombing. Duties such as photoreconnaissance required steady and precise flying at a given altitude and along prescribed flight tracks if the photographs necessary for accurate mapmaking were to be obtained. All the while, the crews had to be constantly on the lookout for enemy air attack, and the steady flight path over enemy territory offered the antiaircraft gunners excellent opportunities for target practice. Certainly the men who flew these aircraft are among the unsung heroes of the First Great War.

The two-seater, as it evolved during the war, had the pilot in the front cockpit with one or two fixed, synchronized machine guns firing between the propeller blades; the observer was in the rear cockpit with one or two flexibly mounted machine guns in addition to the camera, wireless, or other special equipment. A steady platform was required for photoreconnaissance and bomb aiming, which meant that the two-seater had to be relatively stable; yet a certain amount of speed and maneuverability were required to avoid destruction by the enemy. Good high-altitude performance was another desirable characteristic. The correct mix of these sometimes conflicting requirements and the technical means for accomplishing that mix presented difficult design problems. In the early years of the war, two-seaters were often considered to be easy prey for fighter aircraft; but as designs improved, they gave an increasingly good account of themselves in combat operations.

The development of the two-seater presents little of technical interest beyond what has already been discussed in the preceding sections on fighters and bombers. A large number of two-seat types were developed during the war, and a number of configuration concepts, including monoplanes, biplanes, triplanes, and quadruplanes were investigated. As in the case of the fighters and bombers, however, the biplane emerged as the best compromise, consistent with the existing state of technology, between the various conflicting requirements. Three two-seat biplanes, the British B.E.2c, the German Junkers J-I, and the British DeHavilland DH-4 are described next.

B.E.2c

It would be difficult to conceive of an aircraft so poorly adapted to the rigors of aerial combat as the long-lived series of British B.E.2 two-seaters designed by the government-controlled Royal Aircraft Factory. The prototype first flew in 1912, and a B.E.2a was the first British aircraft to land in France, on August 13, 1914, after the beginning of the war. The B.E.2c and other models of the B.E. series remained in production until July 1917. More than 3500 B.E.2-type aircraft were constructed, and, unbelievably, a single-seat fighter version, the B.E.12, was also produced. The British ace Albert Ball referred to this machine in the following succinct terms, ". . . a bloody awful aeroplane."

The B.E.2 was developed on the premise that inherent stability in an aircraft was a highly desirable characteristic that would contribute to flying ease and flight safety. Further, the military thinking in 1914 envisioned the use of the airplane in warfare solely as an instrument for supporting the army ground troops. Again, inherent stability seemed a desirable characteristic for such duties as reconnaissance and artillery spotting. Unfortunately, experience early in the war showed that a two-seater required speed, maneuverability, and a good rate of climb to survive. The B.E.2c had none of these characteristics, yet production of the aircraft continued; it was callously referred to as "cold meat" by German fighter pilots.

As shown in figure 2.24, the B.E.2c was a strut-and-wire-braced, double-bay biplane equipped with an in-line engine swinging a four-blade propeller. The 90-horsepower R.A.F. la engine itself was somewhat unusual in that it was air cooled. Ailerons were incorporated in both upper and lower wings, and the horizontal and vertical tail units had both fixed and movable surfaces. The large dihedral angle evident in the wings was dictated by the requirement for inherent lateral-directional stability. Unlike most two-seaters, the pilot sat in the rear cockpit and the gunner was in the front cockpit. Although the B.E.2c was equipped with a single machine gun, the field of fire between the wings and over the pilot's head and vertical tail limited the gunner's effectiveness. Because of the position of the lower wing relative to the gunner, the pilot had to operate the camera on photoreconnaissance missions in addition to flying the aircraft.

The data in table I show the 2142-pound gross weight of the B.E.2c to have had a disastrously low maximum speed of 72 miles per hour at 6500 feet. Not shown in the table is the climb-performance data that indicate that 45 minutes were required to climb to the low service ceiling of 10 000 feet. The zero-lift drag coefficient, drag area,

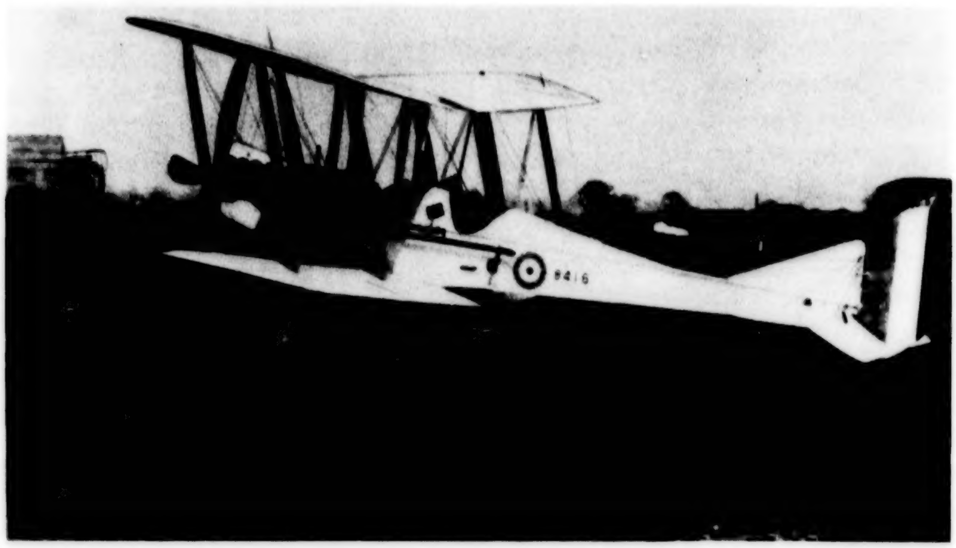

Figure 2.24 — British B.E.2c army cooperation aircraft; 1914. [ukn via Martin Copp]

and maximum lift-drag ratio were comparable to many contemporary aircraft of the time; however, the ratios of power to weight and power to drag area were so low that only mediocre performance could be expected. In addition to its performance limitations, all reference sources indicate that the aircraft lacked maneuverability.

The shortcomings of the B.E.2c in armament, performance, and maneuverability resulted in a very poor front-line aircraft that was almost defenseless against determined enemy air attack. Untold numbers of British airmen perished in this monument to bureaucratic inertia and ignorance. The B.E.2c is presented here, not as an example of a good aircraft or one having significant technical innovations, but as an illustration of how an ineffective aircraft can be produced and fostered on the user long after it is obsolete. Similar examples can be found in the course of aeronautical history.

Junkers J-I

A bewildering variety of two-seat army cooperation aircraft were designed, developed, and operated by the Germans in World War I. Albatros, AEG, Roland, DFW, Halberstadt, AGO, Aviatik, LVG, Junkers, and Rumpler are only a few of the companies that produced

army cooperation aircraft during the conflict. Some of these aircraft were designed for general-purpose reconnaissance duties, others for night bombing, and still others for the ground attack role in close cooperation with friendly ground troops. An interesting aircraft in this latter category, the Junkers J-I, is described here and is shown in figure 2.25.

The J-I biplane had a rather unusual appearance with thick, cantilever wings that were tapered in both planform and thickness ratio. Three-view drawings show that the aircraft was really a sesquiplane, with the bottom wing much smaller in span and chord than the upper wing. The small-chord lower wing, together with its position below the lower surface of the fuselage, afforded good downward visibility for the pilot in the front cockpit and the observer in the rear. The wings were connected to each other and to the fuselage by a rather complex cabane-strut arrangement. No interplane struts were used between the wings. Like all Junkers aircraft, the J-I incorporated an all-metal structure. The wing was composed of 0.08-inch corrugated aluminum alloy skin riveted to an internal framework of aluminum alloy tubing. The engine and crew were encased in an armored shell formed from 0.2-

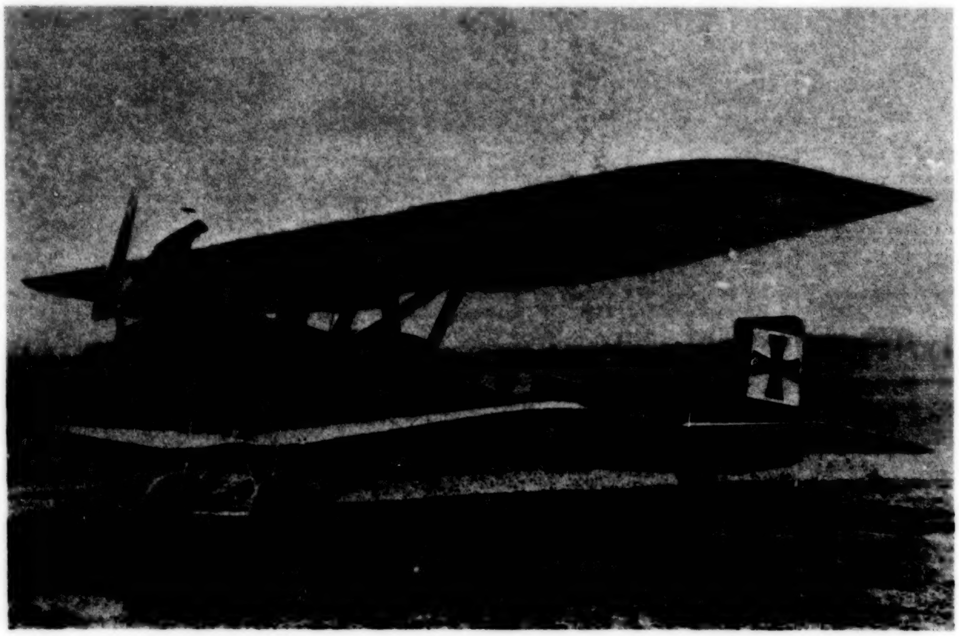

Figure 2.25 — German Junkers J-I all-metal army cooperation aircraft; 1918. [Peter M. Bowers via AAHS]

inch sheet steel. The aft portion of the fuselage consisted of a metal alloy frame covered with fabric in early models but with sheet metal in later versions. Power was provided by a six-cylinder, water-cooled, Benz Bz.IV engine of 200 horsepower. The aircraft was usually armed with two fixed, synchronized machine guns firing between the propeller blades and with a single flexible gun for use by the observer. Two downward-firing guns were sometimes installed for the observer, but the difficulty of aiming these guns from a low, fast-flying aircraft rendered them ineffective, and they were quickly removed. A radio link connecting the aircraft with friendly ground troops in the forward area was also generally provided.

The physical and performance data given in table I indicate that the J-I was a remarkable aircraft in many respects. The gross weight of 4748 pounds seems large for an aircraft of only 200 horsepower, and the useful load fraction of 0.19 is very low compared with the values of 0.30 to 0.35 shown in figure 2.20 for fighter aircraft. A low structural efficiency is accordingly suggested; however, the 0.20-inch steel shell of armor alone weighted 1036 pounds, according to reference 119, and no doubt contributed in large measure to the low apparent structural efficiency. The power loading of 23.9 pounds per horsepower is about the same as that of the B.E.2c and suggests a powered glider more than a fighting aircraft. The J-I, however, had a maximum speed of 96 miles per hour, could climb to 6560 feet in 30 minutes, and had an endurance of 2 hours, a very creditable performance for an aircraft of relatively low power. The good performance of the aircraft was due in large part to the low value of the zero-lift drag coefficient of 0.0335 and the high value of the maximum lift-drag ratio of 10.3. The J-I was among the most aerodynamically efficient of the World War I aircraft analyzed here.

The J-I proved in action to be a very effective weapon in the ground-attack role for which it was designed. The prototype first flew in January 1917, but due to production difficulties the aircraft was not deployed in action until February 1918. Total production run was 227 aircraft. The Junkers J-I incorporated many advanced engineering features and was a truly remarkable aircraft. It has not received proper recognition in the literature of World War I aviation.

DeHavilland DH-4

Although the DeHavilland DH-4 was an ordinary looking, strut-and-wire-braced, double-bay biplane, it occupies a unique niche in avia-

tion history as the only aircraft manufactured in the United States to serve in combat on the Western front in World War I. A total of 4846 DH-4 aircraft were built (under license) in the United States, and about 1600 of these reached France. They were all powered with the U.S.-designed and built 12-cylinder Liberty engine of 400 horsepower. The interesting story of the development of this outstanding engine is described in reference 45.

Two views of the DH-4 are shown in figures 2.26 and 2.27. The legend on the side of the aircraft pictured in figure 2.26 indicates that it was number 1000 off the United States production line and that it would leave (by ship) at 4:30 p.m., July 31, 1918. The DH-4 shown in figure 2.27 was the "pattern aircraft" sent from England to the United States in the summer of 1917 for use in developing production drawings for use by U.S. manufacturers.[1] The photograph was made in the

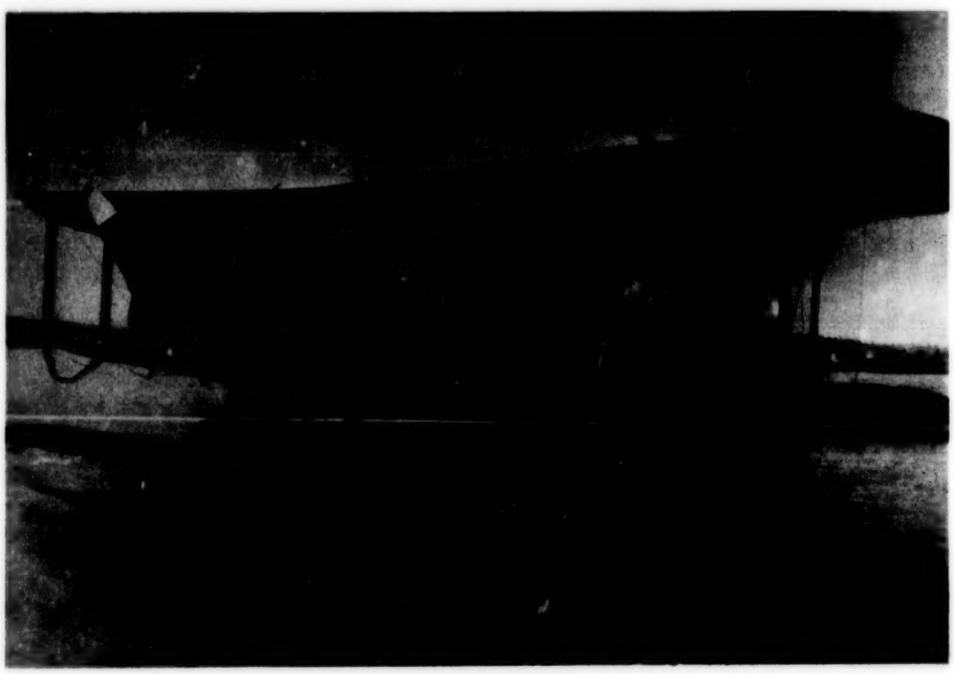

Figure 2.26 — American-built (British-designed) DeHavilland DH-4 army cooperation aircraft; 1918. [Warren Bodie via AAHS]

[1] According to a recent publication, this aircraft has been identified by personnel of the National Air and Space Museum as the first DH-4 manufactured in the United States and is not, as was previously thought, a British-built pattern aircraft. See Boyne, Walter J.: *The Aircraft Treasures of Silver Hill* (New York: Rawson Associates).

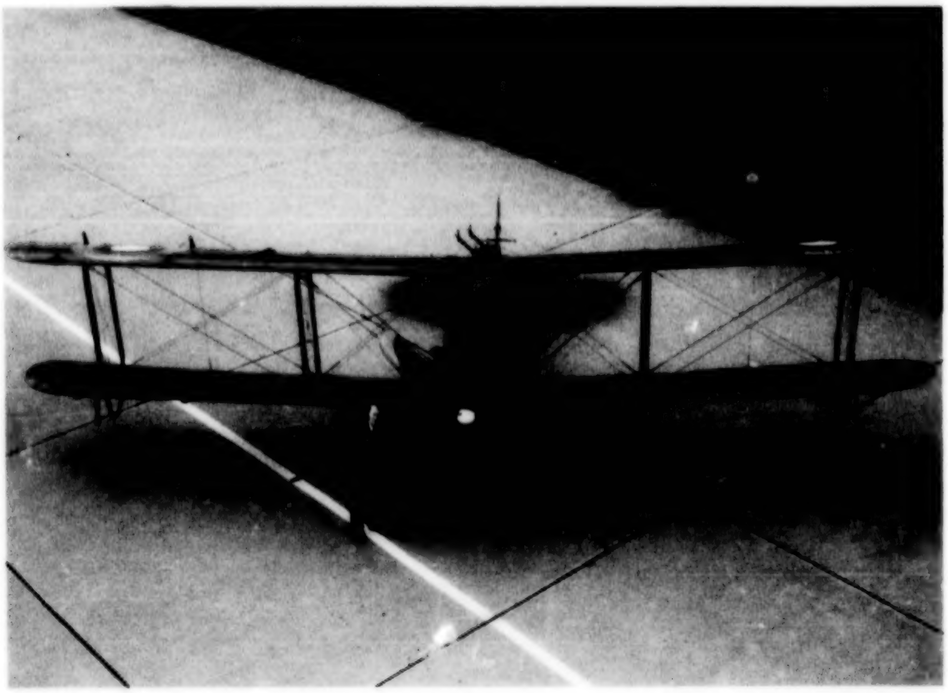

Figure 2.27 — National Air and Space Museum DH-4 on loan to the NASA Langley Research Center in 1967. Dr. Floyd L. Thompson, former Langley director, is shown with the aircraft. [*NASA*]

fall of 1967 when this historic aircraft, on loan from the National Air and Space Museum, was exhibited at the Langley Research Center of the National Aeronautics and Space Administration on the occasion of its 50th anniversary. The gentleman in the photograph is Dr. Floyd L. Thompson, former director and longtime research leader at the Langley center.

The DH-4 was designed as a day bomber and general-purpose reconnaissance aircraft by Geoffery DeHavilland for the Aircraft Manufacturing Company (AIRCO). It first flew in August 1916, was deployed in March 1917, and subsequently served on all British fronts. DH-4's built in Britain were powered with a variety of engines, including the well-known Rolls-Royce Eagle powerplants of 250 horsepower. Only 1440 DH-4 aircraft were built in England.

Figures 2.26 and 2.27 depict a very conventional-appearing biplane. Both photographs clearly show the maze of wires required to support the typically thin wings against flight and ground loads and to hold the wings in proper alignment. The aircraft had a conventional wood-frame structure covered with fabric, except for the forward part of the fuselage which was sheathed in plywood. An unusual feature of the aircraft was the large distance separating the pilot and the observer. The internal volume between the two cockpits was occupied by a large fuel tank. Communication between the pilot located under the top wing and the aft-placed observer was difficult, and the tank between the crew members was rumored to have a propensity for catching fire in an accident or when hit by enemy gunfire. As a consequence, the aircraft was sometimes unflatteringly referred to by crew members as the "Flaming Coffin."

The flight controls, which included ailerons on both upper and lower wings, were entirely conventional with the exception of the fixed portion of the horizontal tail, which could be adjusted in flight with a trim wheel located in the cockpit. The aircraft could accordingly be trimmed for zero longitudinal stick force as speed, weight, and altitude varied during the course of a flight. All modern aircraft have pitch trim capability, but this highly desirable feature was seldom found in World War I aircraft. Another unusual feature in the DH-4 was the tail skid that could be steered with the rudder bar; ground maneuverability was much enhanced by this feature. According to reference 28, the aircraft had light control forces and adequate stability and was easy to fly and land. Armament varied but usually consisted of two fixed, forward-firing machine guns operated by the pilot and two flexible guns for use by the observer. On daylight bombing raids, 10 small bombs were mounted beneath the lower wing, 5 on either side of the fuselage; these bombs are visible in figure 2.27.

The data in table I for the DH-4 are for the Liberty-powered, American-built version of the aircraft. It was a relatively heavy machine with a gross weight of 4595 pounds, but the 400-horsepower engine gave it ratios of power to weight and power to drag area that were nearly the same as those for the Fokker D-VII fighter; the values of the maximum lift-drag ratio of the two aircraft were also nearly the same. Fighterlike performance might therefore be expected of the DH-4, and the maximum speed of 124 miles per hour certainly confirms this expectation. The rather nigh, for its day, stalling speed resulted from the 10.4-pound-per-square-foot wing loading in combination with the low

maximum lift coefficient of the thin wings. The aircraft had a service ceiling of 19 600 feet and could climb to 10 000 feet in 14 minutes.

Termination of hostilities in November 1918 resulted in cancellation of contracts in the United States for an additional 5160 aircraft. The end of the war, however, did not spell the end of the career of the DH-4 in the United States, as is seen in chapter 3.

The Heritage of World War I

Out of the profusion of different configuration types, structural concepts, and propulsion systems explored during the hectic days of World War I, there emerged the strut-and-wire-braced biplane, constructed of wood frame and covered with fabric, as the best overall compromise between structural strength, weight, and aerodynamic efficiency consistent with the existing state of technology. This "standard airplane" formula, with various improvements, was applied to all manner of single and multiengine civil and military aircraft for many years following the end of the war. In fact, one of the most extensively used training aircraft in the United States during World War II was the well-known Stearman PT-17 biplane. Even today, biplanes are flown for sport, aerobatic competition, and crop spraying.

Although a number of biplanes have been described above, a review of some of the salient features of the "standard airplane," the airplane design formula with which most countries entered the decade of the 1920's, may be of interest. By the end of the war, the rotary engine was obsolete, and the in-line, water-cooled type was predominant. Values of the ratio of dry weight to power had been reduced from between 3.5 and 4.0 for early Curtiss and Mercedes engines to 2.5 for the 220-horsepower Hispano-Suiza and 2.0 for the 400-horsepower Liberty. These values were lower than the typical value of 2.7 for the rotaries; however, the values given for the water-cooled engines do not include the weight of the radiator, associated plumbing, or cooling water. The propellers that transformed engine power to propulsive thrust were of fixed pitch design and laminated wooden construction. The limited speed range through which aircraft operated in that era did not warrant the use of any type of variable pitch arrangement. Large diameter propellers, consistent with the low rotational speed of most engines, were used and gave excellent takeoff and climb performance for a given amount of power. Engines were usually started by the simple expedient of having a mechanic swing the propeller by hand.

The callout of "off" and "contact" between the pilot operating the ignition switch in the cockpit and the mechanic turning the propeller was a familiar litany around airports for many years.

The wing loadings of aircraft in those early years were low, usually below 10 pounds per square foot, to allow operation from small fields. Most aircraft could take off and land in a few hundred feet. The typical fixed landing gear had large wheels for operation from soft unsurfaced fields and had no form of streamlining. No brakes were incorporated in the landing gear, and the tail skid was usually a fixed nonsteerable device. The action of the propeller slipstream on the rudder provided the only means of maneuvering the aircraft on the ground; accordingly, mechanics walking at the wing tips were frequently used to assist in ground handling. The tail skid served as a sort of brake on landing rollout as the aircraft moved across the soft unpaved field; it also assisted in keeping the aircraft headed in a given direction. Crosswind operations were rarely undertaken, and most airports were roughly square or circular in shape so that the pilot was always able to take off and land directly into the wind.

The control surfaces of the "standard airplane" were directly connected to the rudder bar and control stick by wires or cables; at least parts of these control lines were usually exposed to the airstream on the outside of the aircraft. Incredibly, the aileron control cables of the DH–4 ran along the leading edges of the wings. Most aircraft had no longitudinal trim system, and means for adjusting lateral and directional trim were unheard of. The relationship between the size of the control surfaces, the desired response characteristics of the aircraft, and the control forces required of the pilot were little understood in 1918. As a consequence, the flying and handling characteristics of aircraft of that day generally varied from poor to terrible as judged by modern-day standards. A fine-handling aircraft, of which there were a few, was more a matter of luck than anything else.

Typically, the crew rode in an open, drafty cockpit exposed to the elements. In fact, pilots of that day and for many years thereafter felt that "feeling the wind in their faces" was necessary in order to fly an aircraft with skill and safety. The cockpits were, of course, unheated with no supply of supplementary oxygen, even though altitudes as high as 20000 feet could be reached by many aircraft. The extreme discomfort experienced by the flight crews at these high altitudes can readily be imagined. The well-equipped pilot's instrument panel usually consisted of oil temperature and pressure gages, water temperature gage, and tachometer. These instruments, together with some sort of fuel

gage, served to indicate the health of the propulsion system. In the way of flight instruments, an altimeter, airspeed indicator, and compass usually completed the instrument panel although a crude type of inclinometer was sometimes included. Radios for navigational purposes were largely unknown. Radios used for communication with ground troops were sometimes carried, and these were powered by a wind-driven generator.

Such were some of the design features of the "standard airplane" that emerged from World War I. Post-World War I aircraft development, discussed in the following chapters, began on a foundation provided by the technology and concepts of the 1918 "standard airplane."

Chapter 3
The Lean Years, 1918–26

Background

The pace of aircraft development and production was extremely slow during the time period from the armistice in November 1918 until about 1926. World War I was thought to be the war "to end all wars," the war "to make the world safe for democracy." Postwar military appropriations, including funds for new aircraft, were accordingly small. The primary financial base underlying the development and production of new aircraft and advanced technology had dried up. The military made use of leftover and modified aircraft from World War I, of which the DeHavilland DH–4, previously described, was a prime example. In fact, the DH–4 continued to serve in various capacities in the Army Air Corps of the United States until the early 1930's. There was, of course, some development activity sponsored by both the Army and the Navy, and a number of prototypes of new aircraft were produced. These prototypes, however, usually followed the familiar biplane formula that emerged from World War I. Some small production contracts, generally no more than 15 or 20 aircraft, were placed with the existing manufacturers for some of these prototypes. Hence, the industry did not entirely collapse.

The requirements of civil aviation during this time period presented little incentive for advanced aircraft developments. No airlines devoted to the transportation of passengers existed in the United States; however, the Government operated a primitive airmail service that linked various cities in the United States, and the first coast-to-coast airmail service was established in 1921. The aircraft employed for carrying the mails consisted mostly of surplus World War I aircraft, with the ubiquitous DH–4 as the mainstay of the operation. Many modifications were made to the DH to make it more suitable for airmail service, and the aircraft was so utilized until at least 1927 or 1928.

General aviation as we know it today existed only in the form of barnstormers. These gypsy pilots roamed the country from town to town offering 5- to 10-minute rides for sums of around $5.00. The aircraft that served as the workhorse for the gypsy pilot was the Curtiss JN-4 or Jenny. This aircraft was a trainer that served during World War I to introduce thousands of neophytes to the mysteries of flying. In the decade following World War I, many young people, children and teenagers alike, were introduced to the wonderful world of flight by the sight of a Jenny gracefully gliding to a landing in a pasture close to the family homestead. Once seen and heard, the sight and sound of this ancient biplane with its slow-turning engine and the whistling noise of the wind through the bracing wires made an indelible impression on many young people in the 1920's and served as a springboard for their later entry into some aspect of aviation. The Jenny was similar in configuration and construction to the DH-4 shown in figures 2.26 and 2.27 (chapter 2), but, instead of having an engine of 400 horsepower, it was equipped with the 90-horsepower Curtiss OX-5 or the 150-horsepower Wright-Hispano. Most models of the Jenny used by barnstormers had the 90-horsepower engine and were designated JN-4D. The aircraft was quite slow and had a cruising speed that did not differ very much from the stalling speed. By today's standards, the handling characteristics of the Jenny would be considered unacceptable (shown by the data in ref. 101). The Curtiss Jennys, however, were available in large numbers following the end of World War I and could be purchased for as little as a few hundred dollars. Obviously, no new aircraft suited to the demands of the barnstormers could be developed and produced for any such ridiculously low price. Thus, the private sector provided no market for the development and production of new aircraft.

A Curtiss JN-4H with the Wright-Hispano engine is shown in figure 3.1, and the characteristics of this version of the Jenny are given in table II (appendix A).

Transport Developments in Europe

In contrast to the slow development of airline aviation in the United States, European air transport began almost immediately after the cessation of hostilities in 1918. The major capitals of Europe were soon connected by primitive passenger-carrying airlines. The aircraft types utilized for carrying passengers were at first hastily converted

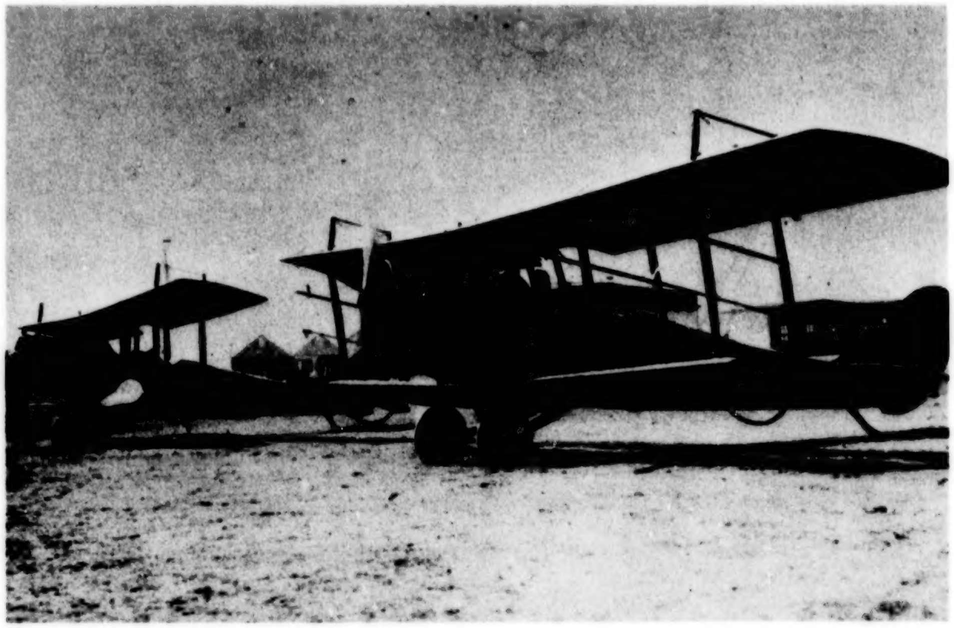

Figure 3.1 — Curtiss JN-4H Jenny trainer; 1918. [NASA]

military bomber and observation types. Later, new aircraft were constructed for the infant airlines; however, these aircraft usually followed the standard biplane formula developed during World War I. Typical of these transport aircraft is the Handley Page trimotor shown in figure 3.2. The aircraft was a multibay biplane, similar in configuration to the bomber types of the war, but employed an enclosed cabin capable of carrying 10 passengers. The two pilots were accommodated in an open cockpit just forward of the leading edge of the upper wing, as can be seen in figure 3.2. Note the four-blade propellers and the multiple wheels of the landing gear. The use of the four-wheel gear was no doubt a concession to the relatively soft sod or mud landing fields of the period. A glance at the characteristics of the aircraft given in table II indicates a relatively heavy machine of 13 000-pound gross weight, but with only 840 horsepower as the combined output of the three engines. The wing loading was a very low 8.9 pounds per square foot in order that the aircraft could operate out of the small fields that existed at the time. The cruising speed was a modest 85 miles per hour; the drag coefficient at zero lift was 0.0549, which was larger than that of the DH-4. Although the use of multiple engines is usually thought to increase safety and reliability, that was not the case with the Handley

Figure 3.2 — Handley Page model W8F 12-passenger trimotor transport; 1924. [Flt. Intl.]

Page trimotor. The aircraft could not maintain level flight following the loss of one engine according to the information given in reference 75. The Handley Page trimotor was put into operation by the British Imperial Airways and the Belgium Sabena Airways Systems in about 1924 and continued in operation, at least to some limited extent, until about 1931. In fact, very large multiengine biplanes were utilized on some European airlines right up to the beginning of World War II.

Aircraft employing the monoplane configuration had been built since the early days of aviation. The first nonstop flight across the English Channel was made in 1909 by Bleriot flying a wire-braced monoplane, and many early World War I fighters were also monoplanes (chapter 2). Most early monoplanes employed a multitude of wires and struts in order to provide strength and rigidity to the wings. As a consequence, the drag characteristics of these aircraft showed little if any improvement compared with contemporary biplane drag characteristics. Furthermore, there seemed to be a lack of confidence in the structural integrity of the monoplane configuration. There were also experiments with internally braced, cantilever monoplanes. As indicated in chapter 2, the German designer Junkers built cantilever monoplanes constructed of metal. The materials and design methods available during World War I, however, did not lend themselves to the construction of light, all-metal cantilever designs. Another early proponent of the cantilever

monoplane was the Dutch designer Anthony H. G. Fokker. Fokker designed and built fighter aircraft for the German Air Force during World War I. His first cantilever monoplane fighter was the model D-VIII, which featured an internally braced wing mounted on struts above the fuselage. (See figure 2.16.)

In 1920 and 1921, Fokker developed a single-engine transport employing an internally braced wing similar in concept to that of the D-VIII fighter. This aircraft, known as the Fokker F-2, is depicted in figure 3.3. The aircraft seated three or four passengers in an enclosed cabin, and a single pilot was located in an open cockpit just under the leading edge of the wing. The absence of external struts and wires to support the wing is obvious from the photograph. The relative aerodynamic cleanliness of the design would be expected to produce a correspondingly low value of the zero-lift drag coefficient. The data in table II, however, suggest that the value of $C_{D,0}$ is not much better for the Fokker than for the DH-4. The open cockpit together with a poor engine installation and consequent high cooling drag suggest themselves as possible reasons for the relatively high zero-lift drag coefficient. The wooden cantilever wing and steel-tube, fabric-covered fuselage formed the basis for a long line of Fokker aircraft built right up to World War II. An improved and larger version of the Fokker F-2, known as the T-2, was the first aircraft to fly nonstop across the United

Figure 3.3 — Fokker F-2 four-passenger transport; 1920. [Flt. Intl.]

States. This flight was made by the U.S. Army Air Service in 1923 (ref. 38). The famous Fokker trimotor was very similar in configuration to the F-2 but employed three modern engines, had a fully enclosed cabin and cockpit, and was much larger than the F-2. The first of the Fokker trimotors was employed by Richard E. Byrd and Floyd Bennett in their historic first flight over the North Pole in 1926.

High-Speed Racing Aircraft

The national and international air races helped stimulate and maintain public interest and support for aviation during the years immediately following World War I. The races also provided a focus for the development of new, high-performance aircraft. Many of these special aircraft were government sponsored. The Army and the Navy sponsored such developments in the United States, as did the air forces of France, Great Britain, and Italy in Europe. The most successful of these aircraft were highly developed forms of the biplane configuration. Typical of such aircraft is the 1923 Curtiss R2C-1 racer shown in figure 3.4. Standing beside the aircraft is Navy Lieutenant Alford J. Williams who flew it to first place in the 1923 Pulitzer race. The aircraft is seen to be extremely clean aerodynamically and had a phenomenally low zero-lift drag coefficient of 0.0206 (table II). The aircraft achieved a maximum speed of 267 miles per hour with a liquid-

Figure 3.4 — Curtiss R2C-1 racer; 1923. [NASM]

cooled engine of about 500 horsepower. Some of the features that accounted for the low drag coefficient and consequent high speed are the minimization of the number of wires and struts to support the wings, the smooth, highly streamlined semimonocoque wooden construction of the fuselage (this type of construction is briefly described in chapter 2 in connection with the Albatros D–III fighter), the all-metal Curtiss Reed propeller, and the very interesting skin-type radiators that were used to provide heat exchange surface for the water-cooled engine. The external surfaces of these radiators, which formed a part of the surface of the wing, were of corrugated skin with the corrugations aligned with the direction of air flow. The remainder of the wing surface was covered with plywood. The Curtiss PW–8 fighter, of which about 30 were produced in the mid-1920's, also employed the skin-type surface radiator. Although the skin radiators contributed significantly to obtaining a low drag coefficient, and hence to improving performance, they were not practical for use on operational combat aircraft. In addition to being prone to leak as a result of flexing of the wings, they were extremely vulnerable to battle damage, which was probably the deciding factor in their elimination from future combat aircraft.

A number of racing aircraft were developed that employed the monoplane configuration. Some of these aircraft had cantilever wings; others employed strut-braced wings; such advanced concepts as retractable landing gear were sometimes seen. For one reason or another, however, none of these monoplane racers was particularly successful. The Dayton Wright RB racer developed for the 1920 Gordon Bennett race was perhaps one of the most advanced concepts developed during the entire period. The aircraft is illustrated in figure 3.5, and some of its characteristics are given in table II. The pilot was entirely enclosed in the fuselage, which was of wooden semimonocoque construction. The cantilever wing was constructed entirely of wood and employed leading- and trailing-edge flaps. These flaps in effect provided variable camber so that the airfoil section could be adjusted to its optimum shape for both high-speed and low-speed flight. This extremely advanced feature did not appear on production aircraft until the development of the jet transport in the 1950's. The landing gear on the Dayton Wright racer retracted into the fuselage in very much the same way as that used in later Grumman fighters of the thirties and forties. The drag coefficient at zero lift of the Dayton Wright racer was 0.0316 (table II), which is considerably higher than the value of 0.0206 for the Curtiss R2C–1 but very much lower than the value of 0.0496 given in table I for the DH–4. Although highly advanced for its time, the

Figure 3.5 — Dayton Wright RB-1 racer; 1920. [NASM]

Dayton Wright racer was not successful in the 1920 Gordon Bennett race. The aircraft was somewhat underpowered and during the race had to withdraw because of a broken rudder cable. Unfortunately, the type was not further developed.

Another highly advanced monoplane racer, developed by the British for the 1925 Schneider trophy race, was the Supermarine S-4. The Schneider race was an international event for seaplanes. Shown in figure 3.6, the S-4 is a beautiful, highly streamlined, cantilever monoplane mounted on twin floats. The wing, constructed of a wooden framework covered with plywood, employed flush radiators that, unlike the previously described Curtiss racer, were not of the skin type. The wings had landing flaps that could be geared to the ailerons. The rear of the fuselage was of wooden semimonocoque construction, and the forward portion containing the engine was of metal. The engine had 12 cylinders arranged in 3 banks of 4. A front view of the engine gave the appearance of the letter "W"; accordingly, this cylinder arrangement was referred to as a W-type engine. A glance at the characteristics of the aircraft contained in table II indicates a drag coefficient of 0.0274, which must be considered quite low in view of the large amount of surface area of the exposed twin floats. The wing loading of about 23 pounds per square foot was high for the period and accounts for the use of the wing trailing-edge flaps. Another important factor that allowed the use of such a high wing loading was the relatively long take-

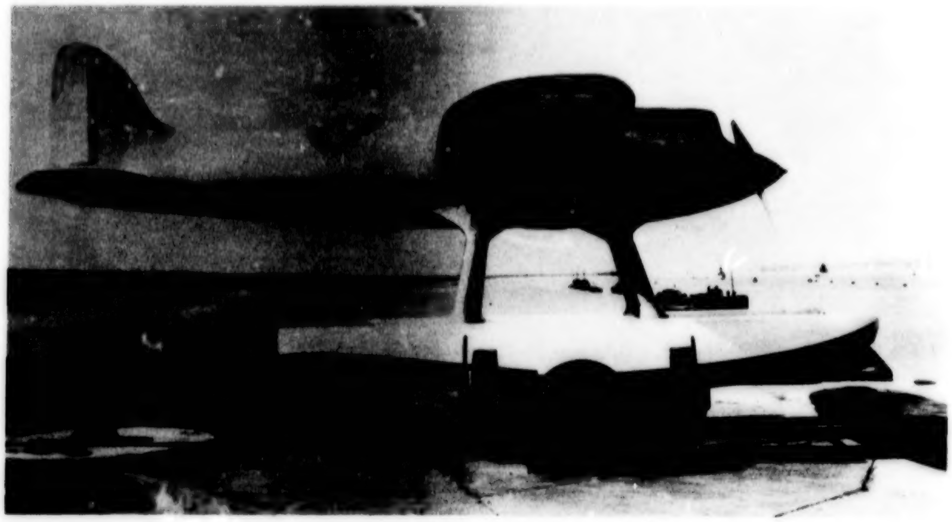

Figure 3.6 — Supermarine S-4 seaplane racer; 1925. [NASM]

off and landing runs possible with the use of rivers and harbors, as compared with the confined land airfields of the day. The aircraft was destroyed by wing flutter before the 1925 Schneider trophy race (ref. 117). According to reference 114, the ailerons on the S-4 were unbalanced, which no doubt contributed to the onset of wing flutter at the high speeds of which the aircraft was capable. Flutter and divergence of cantilever monoplane wings were not understood at that period in the development of aeronautical technology. Later Supermarine racers, which were quite successful in subsequent Schneider trophy competitions, employed the more predictable wire-braced monoplane wings. The designer of the Supermarine S-4, R. J. Mitchell, later designed the famous Spitfire fighter of World War II. For those familiar with the Spitfire, some resemblance between the S-4 and the famous fighter can be seen in figure 3.6. The national and international air races and the aircraft of the early 1920's are described in comprehensive detail by Foxworth in reference 51.

Chapter 4
Design Revolution, 1926–39

Background

The pace of aircraft development began to accelerate by the middle 1920's. Policies were established within the United States that assured consistent, although somewhat small, yearly appropriations for the procurement and development of new military aircraft. In an attempt to improve the poor aviation safety record and thus enhance the image of aviation as a serious means of transportation, laws were enacted that required the licensing of civil aircraft and pilots. Airworthiness standards were developed for the aircraft, and proficiency requirements were established for the licensing of pilots. The aircraft airworthiness requirements opened a market for the development of new types of general aviation aircraft. War surplus aircraft, such as the Jenny, either could not meet the new requirements or their certification would have proved economically unfeasible. The airmail that had been carried by Government aircraft for many years reverted to private contractors. Thus began the airline industry, albeit in a small way. Under the stimulus of these influences, the aircraft industry began to grow.

The pace at which advanced aircraft can be developed is closely coupled to the generation of new and advanced technology. The results of research investigations by the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics (NACA) began to play an increasingly important part in providing the new technology necessary for the development of advanced aircraft. Investigations in aerodynamics, stability and control, propulsion, loads, dynamics, and structures formed the research program of NACA. Wind tunnels, laboratories, flight research, and analytical studies were the means by which new technology was developed. The results of NACA's research investigations were made available to the industry in the form of technical reports. Bound volumes of these reports, covering the

entire lifespan of NACA from 1915 to 1958, are a part of most good technical libraries. Indexes such as those cited in reference 74 give a complete bibliography of research publications by NACA. Years subsequent to 1949 are covered in additional indexes. Brief accounts of the significant research activities of NACA are contained in references 49, 56, and 73.

The universities played an important role in educating young aeronautical engineers and in various aspects of aeronautical research. Schools of aeronautical engineering sponsored by the Guggenheim Foundation were particularly important. These schools existed at the Massachusetts Institute of Technology, the California Institute of Technology, New York University, the University of Michigan, the Georgia Institute of Technology, Stanford University, and the University of Akron. The contributions of the Guggenheim Foundation to the development of aeronautics in the United States are described in reference 70.

The military services played an extremely important role not only in the generation of new technology but in sponsoring the application of that technology in the development of new and useful operating systems. Thus, the development and operation of new military equipment provided a highly significant foundation of proven components, such as engines, for use in new civil aircraft. A summary of the contributions of military aeronautical research and development to the development of advanced commercial aircraft throughout the thirties, forties, and fifties is contained in reference 104. A close relationship can frequently be found between the development of advanced military aircraft and new commercial aircraft that employed not only many of the design features of military aircraft but also hardware and concepts that had been proved in military aviation.

Record Flights

Another important factor in the formula for accelerated development and production of new aircraft were the many record-breaking flights of the time. They were extremely popular with the general public and played an important role in popularizing aviation and its potential as a serious means of transportation. The nonstop solo flight of Charles A. Lindbergh from New York to Paris in May 1927 had the most profound and lasting influence of any of the record-breaking flights. His magnificent flight thrilled and captured the imagination of people all over the world and stimulated an interest and enthusiasm for

aviation that had an incalculable effect on future aeronautical developments. As a result of his flight, a multitude of small companies dedicated to the manufacture of aircraft appeared throughout the United States. Most of these companies flourished for a few years and then quietly passed into bankruptcy as the country entered the Great Depression of the 1930's. Airline operations were given a tremendous boost by the enthusiasm engendered by the Lindbergh flight.

The Ryan monoplane employed by Lindbergh on his historic flight, illustrated in figure 4.1, was of the strut-braced, high-wing type equipped with a fixed landing gear. The fuselage consisted of a welded steel-tube frame, and the wings were of wooden frame construction. The entire aircraft was covered with cloth fabric. The pilot had no forward vision since the space immediately ahead of him was occupied by a large 360-gallon fuel tank. The wheels incorporated no brakes, and the tail skid was of the fixed type. The aircraft utilized the relatively new Wright Whirlwind engine. This engine had nine cylinders radially disposed about the crankcase and crankshaft. In contrast to the rotary engine described earlier, however, the cylinders and crankcase of the radial engine were fixed, and the crankshaft rotated with the propeller attached. The engine developed 220 horsepower and, for its day, was considered to be light and highly reliable. The air-cooled feature re-

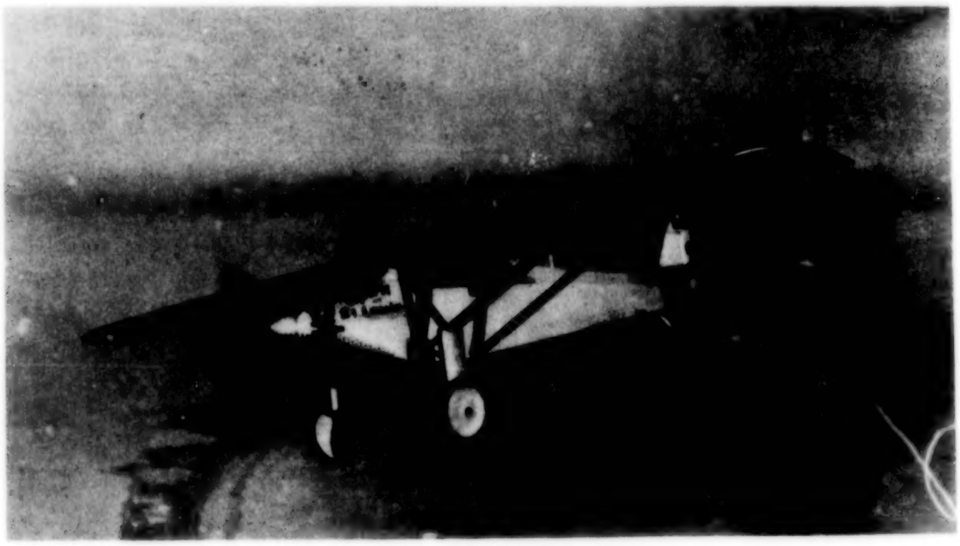

Figure 4.1 — Ryan NYP Spirit of St. Louis; *1927.* [Ryan Aeronautical Library via David A. Anderton]

sulted in the deletion of the radiator and associated plumbing that was always a source of maintenance and reliability problems on liquid-cooled engines. The maximum gross weight of the aircraft was 5135 pounds, and the zero-fuel weight was 2150 pounds. Thus, the fuel in the aircraft represented more than half of the gross weight and gave the *Spirit of St. Louis* airplane a zero-wind range of about 4200 statute miles. The cruising speed of the aircraft was about 95 miles per hour, and the maximum speed, 120 miles per hour. The zero-lift drag coefficient $C_{D,0}$, given in table II (appendix A), was 0.0379. This coefficient represents a considerable reduction over the value of 0.0496 given for the DeHavilland DH–4 but still indicates that the fixed landing gear and multiple wing struts were serious drag-producing elements. The maximum lift-drag ratio of the aircraft was 10.1, which compares favorably with the value of 7.7 given for the DeHavilland 4. The higher effective aspect ratio of the monoplane, compared with the biplane, is in large measure responsible for the increased lift-drag ratio of the *Spirit of St. Louis* compared with the DH–4 and other typical contemporary biplane configurations. A complete description of the *Spirit of St. Louis* giving design and performance data is contained in the appendix of reference 86.

Record-breaking flights continued for many years to play an important role in the development of aviation, particularly as a means of focusing public attention on the possibilities of the aircraft as a safe and reliable means for travel. Long-distance flights, flights around the world, flights of exploration, and, of course, all sorts of air races formed part of the aeronautical scene in the late twenties and thirties. For example, Richard E. Byrd was in command of the first flight over the South Pole in 1929, and Wiley Post circled the globe alone in 7½ days in 1933. The world's absolute speed record was increased to 440 miles per hour in 1934 by an Italian seaplane. The aircraft was equipped with pontoons similar to those shown on the Supermarine S–4 in figure 3.6 and employed wire-braced monoplane wings and a 24-cylinder engine driving two counter-rotating propellers. The absolute speed record was raised to 467 miles per hour in 1938 by the Messerschmitt 209V1 racer. The list of record flights could go on endlessly but will not be continued here. The following paragraphs deal with some of the advanced aircraft that were developed from 1926 to 1939. This era may be characterized as one in which concepts of aircraft design underwent radical change and rapid advances were made in performance.

Monoplanes and Biplanes

The Ryan monoplane *Spirit of St. Louis* pictured in figure 4.1 popularized the monoplane configuration in America and marked the beginning of the decline of the biplane. Another immortal high-wing monoplane, the Ford trimotor, formed the mainstay of the infant U.S. airline industry in the late 1920's and early 1930's. The aircraft, pictured in figure 4.2, featured an internally braced wing, fixed landing gear, and three engines. The basic configuration was similar to the Fokker trimotor referred to earlier; however, the methods of construction employed in the two aircraft were totally different. The Fokker structure consisted of a mixture of wood, metal, and fabric; the Ford was of all-metal construction. The internal structure of the aircraft was entirely of metal, and the skin was a corrugated aluminum alloy. The corrugations provided stiffness in the skin panels and were aligned with the direction of air flow in order to minimize the drag. This type of construction was pioneered by Hugo Junkers in Germany.

The aircraft was produced in two versions: the model 4-AT and the model 5-AT. The aircraft were similar in appearance, but the model 5-AT was slightly larger and employed somewhat more powerful engines than the model 4-AT. Figure 4.2 depicts a model 4-AT, and the specifications given in table II are for the model 5-AT. The model 5-AT carried from 13 to 15 passengers in an enclosed cabin, had a gross weight of 13 500 pounds, and was equipped with three 420-horsepower Pratt & Whitney Wasp radial engines. By this time, the

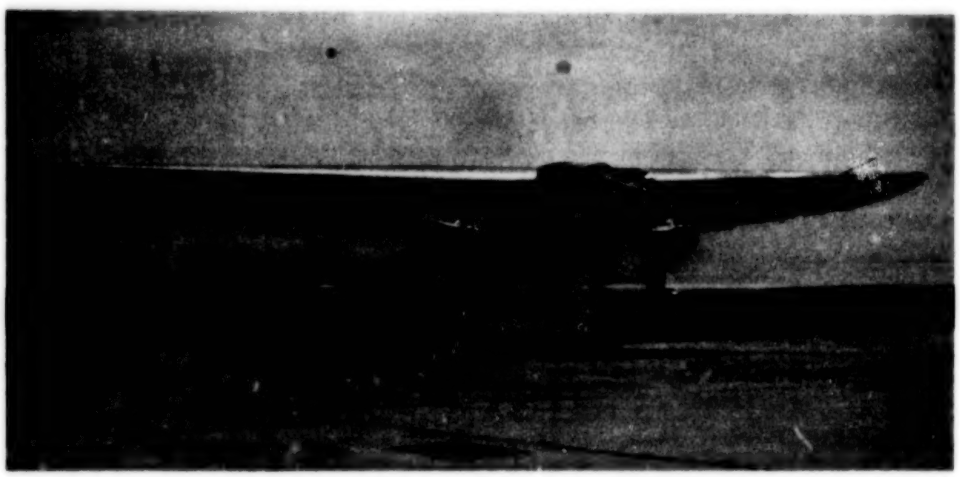

Figure 4.2 — Ford 4-AT 12-passenger trimotor transport; 1928. [NASA]

two pilots were seated in an enclosed cockpit located ahead of the wing. Ground-handling characteristics were enhanced by the provision of differential braking on the main landing gear wheels and a swiveling tail wheel. Cockpit instrumentation was primitive by modern standards, and some of the instruments for the outboard engines were actually located on the engine nacelles, which required the pilots to look out the side windows to read them. The large, powerful engines were equipped with an inertia starter; this type of starter was often used for large engines beginning in the mid-1920's. A flywheel of large moment of inertia was brought to a high rotational speed through the use of either a geared handcrank or an electrical power source. When the proper speed had been reached, a clutch was engaged and the angular momentum of the flywheel caused the engine to rotate and start.

The Ford trimotor was especially designed to maintain flight after the loss of one engine. Under full gross weight conditions, however, the aircraft was not able to climb after takeoff following the loss of an engine, probably because of the excessive drag resulting from the windmilling propeller. Full-feathering propellers had not been developed at that time. The top speed of 150 miles per hour listed in table II for the Ford trimotor may be excessive; cruising speeds somewhat less than 100 miles per hour are indicated in reference 110 for a model 4–AT that is still flying today. The drag coefficient $C_{D,0}$ for the Ford is seen to be relatively high, as compared with that for the Ryan *Spirit of St. Louis.* The drag of the two outboard engines and the nacelles no doubt contributed significantly to the total drag of the trimotor and, to some extent, nullified the advantages of the cantilever wing. Furthermore, according to reference 72, the wetted area of an aircraft may be increased by as much as 20 to 40 percent by corrugations in the metal covering. No account was taken of this increment in calculating the drag coefficient given in table II.

The prototype of the Ford trimotor flew in 1926, and the last production aircraft rolled off the line in 1933. A total of 116 models of the 5–AT and 84 models of the 4–AT were constructed. Some of these aircraft are still flying today, and one was flying in scheduled airline service with the remarkable Island Airlines at Port Clinton, Ohio, into the 1970's. The longevity of these aircraft attests to their rugged construction and basic design soundness.

The Lockheed Vega shown in figure 4.3 was a very high-performance monoplane that first flew in 1927. The aircraft shown in the photograph is a fully developed model 5C version. Both the internal structure and the outer covering of the aircraft were wood. The wing was of

Figure 4.3 — Lockheed Vega 5C mail and passenger plane; 1929. [Peter C. Boisseau]

the internally braced, cantilever type, and the fuselage was of semimonocoque construction. A new feature, which appeared on this aircraft, was a circular cowling surrounding the 450-horsepower Pratt & Whitney Wasp air-cooled engine. This cowling concept was one of NACA's early contributions and provided substantial increases in the speed of aircraft employing radial engines, but, at the same time, directed the cooling air through the engine in such a way as to provide adequate cooling. The maximum speed of the Lockheed Vega was increased from 165 miles per hour to 190 miles per hour by the addition of the NACA cowling. Fairings, called pants, around the wheels of the landing gear also reduced the drag and resulted in an increase in the speed of the aircraft. The Lockheed Vega had a very low zero-lift drag coefficient of 0.0278, as shown by the data in table II. The low zero-lift drag coefficient was obtained through careful attention to detailed aerodynamic design of the aircraft and by the absence of drag-producing struts, wires, and other external drag-producing elements. The fixed landing gear, however, remained as a significant drag-producing feature of the airplane. The maximum lift-drag ratio of the Vega was 11.4, which was unusually high for that time period. The Lockheed Vega was used in airline service (six passengers) and was also employed in many record-breaking flights. The aircraft shown in figure 4.3 is painted to represent the famous *Winnie Mae,* which Wiley Post flew solo around

the world in about 7½ days in the summer of 1933. The actual aircraft Post flew on this remarkable flight is in the National Air and Space Museum in Washington, D.C. The Lockheed Vega was a highly advanced and refined design for its day, and, even now, the performance is very good for an aircraft with fixed landing gear.

The demise of the Jenny and its contemporaries opened the way for a new generation of general aviation aircraft for fixed-base operators and barnstormers. Most of these new aircraft employed a welded steel-tube fuselage and wooden wing structure and incorporated a fabric covering over the entire structure. The aircraft depicted in figures 4.4 and 4.5 are typical of the classes of aircraft produced during the latter part of the 1920's. The Curtiss Robin shown in figure 4.4 was designed along the lines of the strut-braced monoplane formula popularized by Lindbergh's *Spirit of St. Louis*. The aircraft was ruggedly built with a view toward operation from poorly prepared airfields or pastures. The enclosed cabin provided seating for a pilot in the front and two passengers in the rear seat. The aircraft was usually equipped with either a Curtiss Challenger six-cylinder radial engine or a Wright J6-5 five-cylinder radial engine. The specifications given in table II are for the Challenger-powered Robin, which had 185 horsepower and was capable of a maximum speed of 115 miles per hour. The aircraft was fitted with wheel brakes and a steerable tail wheel or skid. The drag coefficient of the Robin was a very high 0.0585, which probably resulted from the very large cylinders of the exposed radial engine, the many sharp corners of the forward-facing windshield, and the relatively unfaired junctures between the multitude of struts supporting the wings

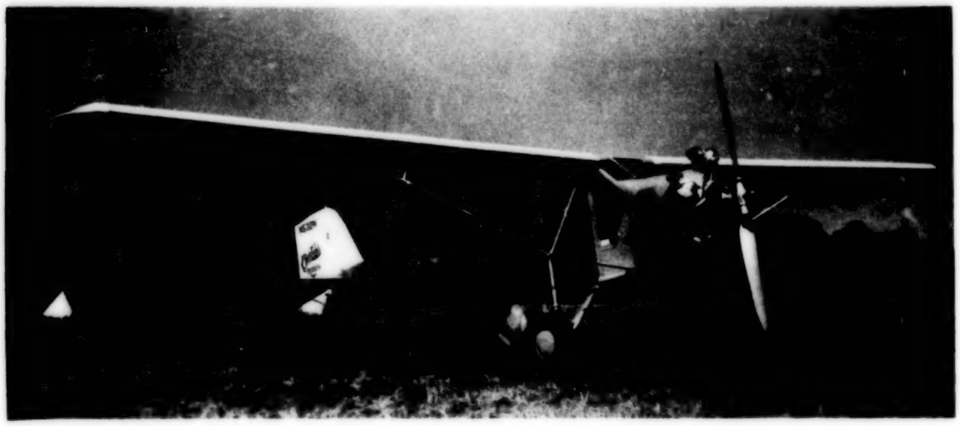

Figure 4.4 — Curtiss Robin three-place-cabin monoplane; 1929. [Peter C. Boisseau]

Figure 4.5 — Travelair 4000 three-place open-cockpit biplane; 1928. [Peter C. Boisseau]

and landing gear. The zero-lift drag coefficient of the Robin is seen to be more than 0.020 greater than that of the Ryan *Spirit of St. Louis*.

The biplane type was still popular and is illustrated by the Travelair 4000 of 1928 shown in figure 4.5. The aircraft was typical of a large number of three-place open biplanes in which the pilot sat alone in the rear cockpit and two passengers were placed forward under the wing near the center of gravity in an open front cockpit. The aircraft is seen to employ struts and wires for bracing the wings, but they are far fewer in number than those used on the typical World War I biplane represented by the DH–4 pictured in figures 2.26 and 2.27. Many different power plants were used in the various open cockpit biplanes produced in the late 1920's. The venerable Curtiss OX–5 water-cooled engine of World War I fame was still available in large numbers and formed a cheap source of power plants for new aircraft. Engines of higher power and greater reliability, such as the Wright Whirlwind, were also available, but these engines were considerably more costly than the surplus World War I engines. The Travelair 4000 shown in figure 4.5 has the Wright Whirlwind nine-cylinder radial engine. The large horn-balanced ailerons and rudder on the Travelair are particularly noteworthy. Bal-

anced controls of this type were used on the World War I German Fokker D-7, figure 2.14, and formed a distinctive identifying feature of the aircraft. For this reason, the Travelair 4000, which was manufactured in Wichita, Kansas, is often referred to as the Wichita Fokker. Aircraft of the vintage of the Curtiss Robin and the Travelair 4000 are highly prized antiques today and are the subject of painstaking restoration. The Robin was used in the 1920's and 1930's in several record-breaking endurance flights, and in the late 1930's it was flown nonstop across the Atlantic by Douglas Corrigan.

Meanwhile, the military services remained wedded to the biplane concept for their fighters, observation planes, bombers, and other classes of aircraft. One of the last biplane fighters developed for the U.S. Army Air Corps, and one of distinctly elegant design, was the Curtiss Hawk P-6E shown in figure 4.6. This aircraft traces its lineage back to the Curtiss Hawk P-1 of 1925, which in turn was derived, at least in part, from the Curtiss racing aircraft of that period. The P-6E was the last of the biplane line of Hawk fighters built for the U.S. Army Air Corps. Various versions of the Hawk were also procured by the U.S. Navy and a number of foreign countries. The entire Hawk series employed tapered wings, and the model P-6E featured a low drag, single-strut landing gear together with a carefully streamlined installation of

Figure 4.6 — Curtiss Hawk P-6E fighter; 1931. [Peter C. Boisseau]

the 650-horsepower Curtiss conquerer engine. The construction of the aircraft was conventional; the fuselage was of the welded steel-tube type, and the wings were constructed of a wood framework. The entire aircraft except for the engine cowling, wing leading edges, and other special portions was covered with fabric. The P–6E was one of the first fighters to employ a droppable auxiliary fuel tank mounted under the fuselage and was equipped with wheel brakes and onboard oxygen equipment. The engine was liquid cooled and employed a chemical known as ethylene glycol rather than water as the coolant. This chemical is essentially the same as the antifreeze used in modern automobile engines. The drag coefficient of the Hawk was a relatively low 0.0371. A comparison of this coefficient with the corresponding value for the Ryan *Spirit of St. Louis* indicates that a well-designed biplane could be as efficient from the point of view of friction drag as a multistrutted monoplane. The lower effective aspect ratio of the biplane wing cell, however, gives a substantially lower maximum lift-drag ratio for the Hawk than for the *Spirit of St. Louis.*

The Hawk model P–6E made its first flight in 1931. A transitional monoplane fighter designed by Boeing was first flown in 1932. This aircraft, known as the P–26 or Pea Shooter, is shown in figure 4.7. The aircraft was a wire-braced monoplane design that incorporated a fixed landing gear and open cockpit but was of all-metal construction, including the skin. The cowling around the engine, known as a Townend ring, reduced the drag of the radial engine but was not as effective as

Figure 4.7 — Boeing P–26A fighter; 1932. [NASA]

the full NACA type of cowling discussed in connection with the Lockheed Vega. The aircraft in its original form had a relatively high landing speed; consequently, all production versions were equipped with simple trailing-edge flaps to reduce the landing speed. This was the first fighter aircraft developed in the United States to employ landing flaps. Thus, the P-26 represented a strange collection of the old and the new in airplane design and was an anachronism when it went into production in 1934. The zero-lift drag coefficient of the Boeing P-26A given in table II is seen to be higher than that of the Curtiss Hawk biplane; however, the drag area of the P-26 is only about 60 percent of that of the Hawk. The P-26 was a transitional type of fighter and had a relatively short service life. Most of the P-26's had been recalled from first-line service by the beginning of World War II, although at least one P-26 flown by a Philippine pilot is thought to have engaged a Japanese fighter in the early days of World War II.

Synergistic Developments

The Lockheed Vega, illustrated in figure 4.3, represented the highest level of aerodynamic efficiency achieved by a high-wing monoplane with fixed landing gear by the year 1930. Reduction in drag and subsequent improvements in the performance of a monoplane such as the Lockheed Vega could obviously be achieved by retracting the landing gear. Retraction of the landing gear on a high-drag aircraft, such as the DH-4, would result in very little improvement in performance since the drag contribution of the landing gear was a relatively small percentage of the total drag coefficient. On an aircraft such as the Lockheed Vega, however, which was characterized by cantilever wings, highly streamlined fuselage, and efficiently cowled engine, the drag of the landing gear would be expected to be a significant portion of the total drag; hence, retraction of the gear would be expected to give a large increment in performance.

The Lockheed Orion, shown in figure 4.8, took this next step in improving aerodynamic efficiency. The Orion was a six-passenger, low-wing monoplane, with the pilot located in an enclosed cockpit forward of the wing. The method of construction employed in the Orion was the same as that utilized in the Vega. The low-wing configuration was particularly adaptable for the use of a retractable landing gear. The gear could be kept short and thus light, and the wing provided an ideal stowage space for the gear in the retracted position. The steerable tail wheel was also retractable in order to provide further increases in aero-

Figure 4.8 — Lockheed Orion 9D mail and passenger plane; 1931. [mfr]

dynamic efficiency. The engine on this aircraft, as on the Vega, employed a single-speed, geared blower to provide improved engine power output at the cruise altitudes of the aircraft. The data in table II indicate that the Orion had a maximum speed of 226 miles per hour at sea level and a cruising speed of 200 miles per hour. The corresponding value of the zero-lift drag coefficient $C_{D,0}$ is 0.0210. The value of this coefficient is seen to be remarkably low, even when compared with values for present-day aircraft; and a comparison with corresponding values for the Lockheed Vega gives a good indication of the magnitude of the improvement in aerodynamic efficiency realized by retracting the landing gear. The retractable landing gear had been thought for many years to be too heavy for practical use in aircraft design; however, the spectacular reductions in drag associated with its use on an aerodynamically clean aircraft were found to far outweigh the relatively small increases in weight. The Orion first flew in mid-1931 and was produced in only limited quantities, perhaps because it was not really large enough for an airline transport; then too, there was a growing feeling that airline aircraft should be equipped with multiengines. Later in the 1930's Government regulations disallowed the use of single-engine aircraft for scheduled passenger-carrying operations.

The configuration and design details of the Lockheed Orion represented an extremely high level of aerodynamic efficiency, a level that